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Optimal Floating Vertical-Axis Wind Turbine Platform Identification, Design, and Cost Estimation

Chad Searcy, Steve Perryman, Dilip Maniar, D. Todd Griffith, Brandon L. Ennis

Prepared by
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Abstract

This report houses the deliverables provided by Stress Engineering Services on the floating platform design identification studies and the detailed final design iterations. The results were obtained under contract to and in partnership with Sandia to iterate between the platform design and the aero-hydro-elastic load simulations of the coupled vertical-axis wind turbine system. Through the analysis summarized in this report, a tension-leg platform with multiple columns was identified as the optimal platform when considering cost and performance. The detailed design and cost estimate of this platform architecture was produced in the final phase of study which is also described within this report.

Acknowledgment

This work was funded by the Wind Energy Technologies Office within the US Department of Energy.

The authors would like to thank Kelley Ruehl and Carlos Michelen from the Water Power Department at Sandia for their assistance with the Phase 1 platform design review. The authors would also like to acknowledge Budi Gunawan and Sara Bredin from Sandia National Laboratories for providing the representative site's characteristic current and wave distributions from buoy data.

Document Revisions

Date	Version	Description
16-Aug-2018	1.00	Initial release.

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Contents

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Introduction

The offshore vertical-axis wind turbine project led by Sandia was performed to assess whether the trends and future development in the wind energy industry would be aided by considering this deviation from the traditional horizontal-axis wind turbines which dominate land-based installations. Both the continual move towards higher capacity machines and the anticipated development of deep-water, offshore sites which require floating platforms provide advantages for vertical-axis wind turbines, where platform costs represent the main single contributor to the total system costs. The goal of this project has been to produce better understanding of the technical and economic feasibility of the floating vertical-axis wind turbine technology solution for offshore wind. Floating vertical-axis wind turbines have many inherent advantages that show promise for reducing costs over floating wind systems using conventional horizontal-axis wind turbines. However, the technical and economic feasibility had been largely unexplored in a comprehensive manner, and it has been the purpose of this project to determine the challenges and opportunities for vertical-axis wind turbines at offshore sites where floating systems are required. The project was conducted in two phases, which are summarized by two reports. The first phase was conducting design studies using a variety of rotor architectures and platform types to assess the feasibility of the technology at this scale. The design studies, methodologies, and findings are described in the full report [1]. Phase two of the project was performed to gain more confidence in the system cost analysis, with a focus on the platform design and cost estimate. The platform selection and design represents a large body of work from this study, which was performed in collaboration with a consultant from the oil and gas industry. The resulting system levelized cost of energy was then studied using the highest fidelity of sources available for each of the capital and operational expenses for the offshore wind plant with floating vertical-axis wind turbines [2].

Focus of platform design studies

For floating offshore wind plants, the platform is the single largest contributor to the system levelized cost of energy (LCOE). The second phase of the offshore vertical-axis wind turbine (VAWT) project was focused on improving the system LCOE estimates through improved estimates on the platform design and cost. To accomplish this, a competitive contract was awarded to Stress Engineering Services (SES) to perform platform design and cost estimation. SES is a consultant based in Houston, Texas that has design experience supporting the offshore oil and gas industry. This report catalogs the deliverables provided by SES throughout the design process, which was performed in collaboration between SES and Sandia.

The platform design work was carried out in two phases. The first phase of study was performed to identify the optimal platform architecture for the VAWT system, which was unknown at the beginning of this project. The Phase 1 studies surveyed numerous floating platform architectures including novel systems which had low technology readiness levels. Six platforms representing the range of stability mechanisms available to floating systems were selected for the initial comparison as summarized in Appendix A. A tension-leg platform with multiple columns was identified as the lowest cost platform from the Phase 1 studies, with interesting performance benefits resulting from the small platform roll/pitch motions.

The second phase of study had the objective of producing a more final design of the selected platform, including dynamic loads simulations. This phase iterated between SES platform design and Sandia aero-hydro-elastic simulations until the platform sizing converged, as described in Appendix B. The final platform design was then used with proprietary cost data from the oil and gas industry to produce a more detailed cost estimate as described in Appendices B and C. A summary of the platform identification and cost estimates is also provided in Reference [2].

References

[1] Griffith, D. T., Barone, M., Paquette, J., Owens, B., Bull, D., Simao-Ferriera, C., Goupee, A. and Fowler, M., "*Design Studies for Deep-Water Floating Offshore Vertical-Axis Wind Turbines*," Tech. Rep. SAND2018-7002, Sandia National Laboratories, 2018.

[2] Ennis, B. L. and Griffith, D. T., "*System Levelized Cost of Energy Analysis for Floating Offshore Vertical-Axis Wind Turbines*," Tech. Rep. SAND2018-9131, Sandia National Laboratories, 2018.

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Appendix A

Phase 1 Platform Design and Identification

Platform and Mooring System Design for a Vertical Axis Wind Turbine (VAWT)

Phase 1 Design Review

21 March 2016

Prepared for: Sandia National Laboratories

Prepared by: Chad Searcy, PhD, PE

Steve Perryman, PE

Reviewed by: John Chappell, PE

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SES Document No.: 1102668-EN-PT-0001 (Rev B)

Background

- Project Motivation
  - Sandia National Laboratories and its partners in government, academia, and industry have been investigating the economic potential and technical feasibility of floating offshore vertical axis wind turbines (VAWTs). In an offshore setting, VAWTs offer multiple cost-competitive advantages over other rotor configurations, namely horizontal axis wind turbines (HAWTs). These advantages are due primarily to having a unique arrangement which places the gearbox, generator, and other related components at the base of the turbine. This placement locates high maintenance systems close to the ocean surface which enhances maintainability and helps reduce the cost of energy. More importantly, this placement lowers the topside center of gravity which enables designers to meet platform stability requirements using smaller and less costly platforms.

- Project Objective
  - In an effort to gain further confidence in the economic viability of floating offshore VAWTs, Sandia National Laboratories has requested Stress Engineering Services, Inc. (SES) to help identify and evaluate the technical performance of potential platform and mooring system designs for a floating offshore VAWT installed in water depths around 150 m. The primary objective of this study is to reduce the uncertainty in the estimated costs associated with the fabrication and installation of a floating offshore VAWT.

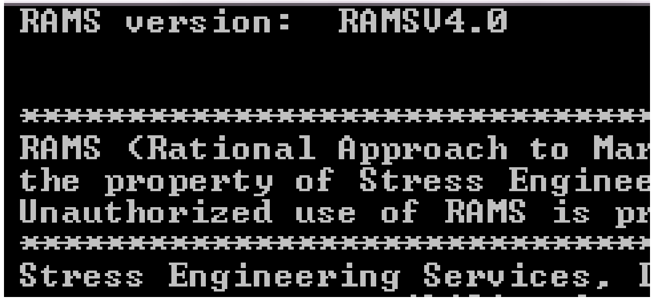
Introduction

Stress Engineering Services, Inc.

- About Stress Engineering Services
  - Stress Engineering Services (SES) is an employee-owned engineering services company founded in 1972. As such, SES renders totally independent and unbiased engineering solutions and opinions. The company, which has office facilities and laboratories in Houston, Cincinnati, New Orleans, and Singapore, has a present staff of 400+ with engineers numbering 220+. Our engineers are highly trained with roughly 67% holding advanced degrees, and highly experienced with about 25% having more than 20 years of experience.
- Design Experience
  - SES has been a leading provider of floating systems solutions for over 40 years. We have extensive experience working with clients in the oil & gas industry on the development of offshore floating platform and mooring system design. Our technical distinction and advanced software programs uniquely position us to successfully optimize the performance, reliability, and safety of your floating system.

Stress Engineering Services, Inc.

- Design Tools
  - At the core of our floating system analytical capability is our proprietary in-house dynamic analysis program, RAMS (Rational Approach to Marine Systems). Unlike other analysis tools, it performs fully coupled dynamic analysis of floating systems with the mooring and floating host platform all connected in a single model. The capability of RAMS – combined with our renowned expertise in testing, mooring design/analysis, reliability, and materials – uniquely positions us to provide a comprehensive range of services.
- Design Philosophy
  - A floating system is a complex assembly of platforms, moorings, controls, and instrumentation. In all phases, from feasibility through execution, it must be designed and treated as a system. SES operates from this system perspective, whether designing the individual parts or integrating them into a whole. SES is also highly qualified to perform the coupled analyses that are essential to making well-informed system decisions.



Phase 1 Scope

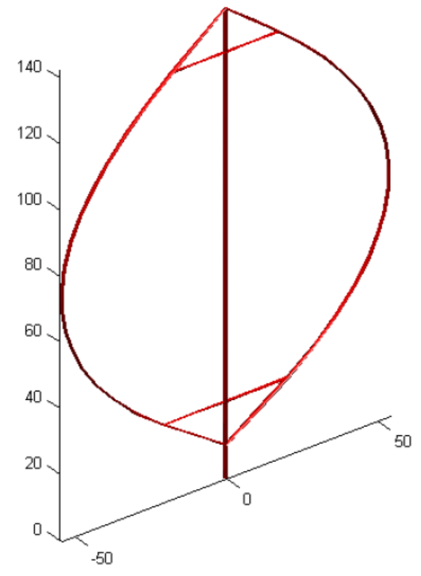
- Develop Design Conditions and Constraints
  - Sandia National Laboratories, in working with Stress Engineering Services, has developed the following categories of design conditions and constraints for the platform and mooring system:
    - Topside Properties (i.e., combined mass, inertia, center of gravity, center of pressure of the turbine, rotor, generator, etc.)
    - Site Definition (i.e., geographic location of the platform, water depth, metocean criteria for design conditions)
    - Maximum Static and Dynamic Loads (i.e., thrust loads, overturning moments).
    - Preliminary Static and Dynamic Motion Requirements (i.e., surge, sway, heave, pitch, roll, yaw) of the floating platform.
- Develop Metrics for Evaluating Phase 1 Concepts
  - Stress Engineering Services, in working with Sandia National Laboratories, has developed a set of metrics for qualitatively evaluating the relative advantages and disadvantages of the Phase 1 floating system concepts based on:
    - System performance, reliability, and risk
    - Cost of fabrication, commissioning, transportation, installation, and integrity management
    - Operational and structural considerations (i.e., support layout, global footprint, access requirements, transmission lines, susceptibility to fatigue, etc.)
- Identify and Evaluate Concepts for Phase 1 Design
  - Stress Engineering Services, after considering dozens of potential candidates platforms, has identified six floating platform concepts for Phase 1 design. Using primarily spreadsheet calculations based on first-principles, each concept has undergone an evaluation to establish its fundamental performance characteristics. Preliminary cost ranges have also been evaluated.

Topside Properties

[2] Topside Properties – DC_2B_LCDT

Sandia National Laboratories

	DC_2B_LCDT
Tower Height Extension (m)	10
Rotor Mass (kg)	220,800
Drivetrain Mass (kg)	298,000
Additional Mass (kg) e.g. pumps, cabling – est	50,000
Total Topside Mass (kg)	568,800
CG (m)	22.5
Mass Moment -- Yaw (about base)	3.48E+07
Mass Moment -- Roll (about base) IRO (kg-m^2)	1.09E+09
Mass Moment -- Pitch (about base) IPO (kg-m^2)	1.13E+09
Mass Moment -- Yaw (about CG)	3.48E+07
Mass Moment -- Roll (about CG) IRC (kg-m^2)	8.08E+08
Mass Moment -- Pitch (about CG) IPC (kg-m^2)	8.41E+08
Center of Pressure (m)	76.0
Cutout Max Thrust Load (kN)	1043
Cutout Mean Thrust Load (kN)	580
Overturning Moment @ Cutout (kN-m) -- Max	7.93E+04
Overturning Moment @ Cutout (kN-m) -- Mean	4.41E+04
AEP (MW-hr)	18,443
Number of Blades	2
Turbine Type	Darrieus
Chord size	Large
Taper at blade root	Double Taper



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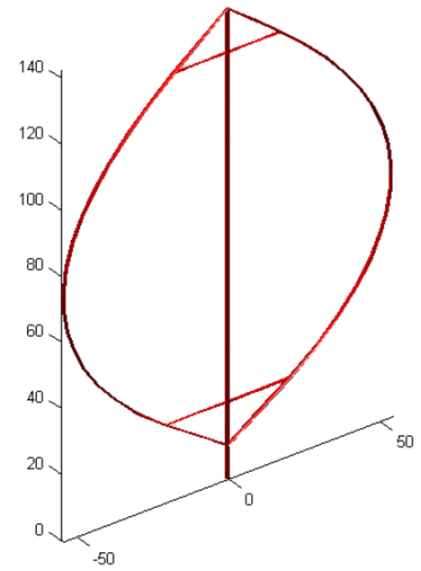
Topside Torque Characteristics

[3] Topside Torque Input – DC_2B_LCDT

Sandia National Laboratories

	DC_2B_LCDT
Tower Height Extension (m)	10
Center of Pressure (m)	76.0
Cutout Max Thrust Load (kN)	1043
Cutout Mean Thrust Load (kN)	580
Overturning Moment @ Cutout (kN-m) -- Max	7.93E+04
Overturning Moment @ Cutout (kN-m) -- Mean	4.41E+04
Max Rotor Torque (kN-m) at 5.5 MW Rotor Power	7.29e3
Max RPM	7.2
AEP (MW-hr)	18,443
Number of Blades	2
Turbine Type	Darrieus
Chord size	Large
Taper at blade root	Double Taper



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Input Data

Drivetrain Mass Estimate

Drivetrain Mass Estimation (2)

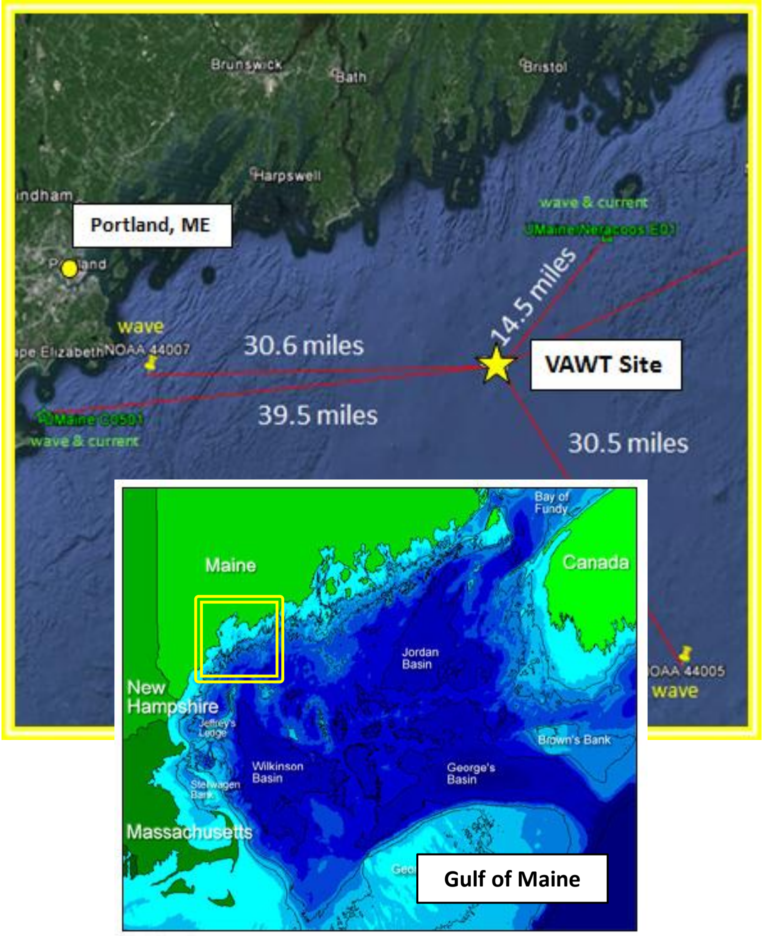
Sandia National Laboratories

Component	Description	Mass Estimate	Justification / Source
Gearbox	For geared system	0	Direct Drive System
Generator	DD Generator	182 tons	Reference [3]: direct-drive generator with 25 kg/kN-m of torque
Mainframe (bedplate support)	Bedplate/structural support; this will be smaller for VAWT	62 tons	Reference [2] 5MW mainframe was upscaled; assumed 50% of this value for VAWT
Low speed shaft	Transfers power from tower to Generator	37 tons	Reference [2]: upscaling of 5MW HAWT low speed shaft mass
High speed shaft	For geared system	0	Direct Drive System
Main Bearings		12 tons	Reference [2]: upscaling of 5MW bearings mass
Yaw System	N/A for VAWT	0	VAWT does not require yaw system
Nacelle Housing	N/A for VAWT	0	Platform hull shall provide covering
Mechanical Brake	Assume larger for VAWT	5 tons	Reference [2]: 5MW HAWT brake of 1 ton; conservative VAWT est.
Total Mass:	**--**	**298 tons**	**--**

Note: Mass estimates are in metric tons (tonnes).

Site Definition

- Gulf of Maine Site
  - Water Depth: 150 m
  - Semi-diurnal Water Depth Variation: 4 m
  - Metocean for Phase 1 Design:
    - 50-year Return Period
    - Significant Wave Height, H_s : 8.0 m
    - Significant Wave Period, T_p : 10.0 s
    - Current: *to be determined*
- Site Impact on Phase 1 Design
  - Freeboard
    - The design freeboard, which is the nominal vertical distance between the mean water surface and the bottom of the turbine blades, was estimated based on the design storm significant wave height and the semi-diurnal water depth variation.
    - Design Freeboard: 15 m (for non-TLPs), 20 m (for TLPs)
  - Mooring
    - Water depth impacts the design and material requirements of mooring
  - System Natural Periods
    - The natural periods of each floating system are checked against the peak period of the design wave spectrum.



Distance from VAWT Site to Port: 25 km (15.6 miles)

Input Data

Selection of Phase 1 Concepts

- Survey of Candidate Platforms
  - Dozens of existing FOWT platform concepts were surveyed including:
    - WindFloat – Principle Power
    - Damping Pool – IDEOL
    - VERTIWIND – Technip/Nenuphar **VAWT**
    - Tri-Floater – GustoMSC
    - SPINFLOAT – EOLFI/GustoMSC **VAWT**
    - Nautilus Semi-Sub – Naultilus Floating Solutions
    - Nezzy SCD – Aerodyn Engineering
    - TetraFloat – TetraFloat Ltd.
    - VolturnUS – DeepCWind Consortium
    - Compact Semi-Sub – Mitsui Engineering & Shipbuilding
    - V-Shape Semi-Sub – Mitsubishi Heavy Industries
    - Hywind – Statoil
    - Sway – Sway A/S
    - Hybrid Spar – Toda Construction
    - Advanced Spar – Japan Marine United
    - SeaTwirl – SeaTwirl Engineering **VAWT**
    - DeepWind Spar – DeepWind Consortium **VAWT**
    - PelaStar – Glosten Associates
    - Blue H TLP – Blue H Group

Source: Carbon Trust, "Floating Offshore Wind: Market and Technology Review," June 2015.

Selection of Phase 1 Concepts

- Survey of Candidate Platforms (continued)
  - The wide variety of surveyed platforms were qualitatively evaluated according to several criteria including:
    - Concepts are described in enough clarity to allow assessment with spreadsheets
    - Field -proven hull/mooring performance
    - Suitability to the unique loading from a VAWT
    - Potential sensitivity to hydrodynamics
    - Redundancy in mooring and vessel buoyancy
    - Ability to tow-out with topsides fully installed
    - Water depth scalability
    - Potential sensitivity to fatigue
    - Amenable to mass production
    - Simplicity over complexity with robustness to survive in the open ocean
    - Innovation which can lead to lower cost of electricity

Source: Carbon Trust, "Floating Offshore Wind: Market and Technology Review," June 2015.

Selection of Phase 1 Concepts

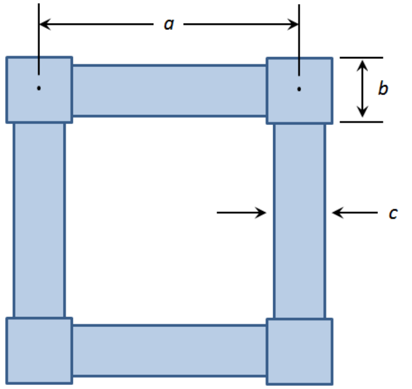
- Overview of Selected Concepts
  - Concept #1: Four-column Semi-submersible
    - This traditional concept has extensive field-proven performance and offers the ability to tow-out with topsides fully installed.
  - Concept #2: Classic Spar
    - This traditional deep-draft concept has extensive field-proven performance and is amenable to mass production.
  - Concept #3: Ring Pontoon
    - This novel water-plane stabilized concept was chosen for its simplicity of design and its potential ability to tow-out with topsides fully installed.
  - Concept #4: Compact Semi-submersible
    - This novel variant of the traditional semi-submersible may offer comparable performance with reduced material costs.
  - Concept #5: Advanced Spar
    - This novel variant of the classic spar potentially offers comparable performance with the ability to tow-out with topsides fully installed.
  - Concept #6: Multi-cellular Tension Leg Platform
    - TLPs, in general, exhibit low roll/pitch motions which will favor maximum energy capture. This multi-cellular hull concept is amenable to mass production.

Source: Carbon Trust, "Floating Offshore Wind: Market and Technology Review," June 2015.

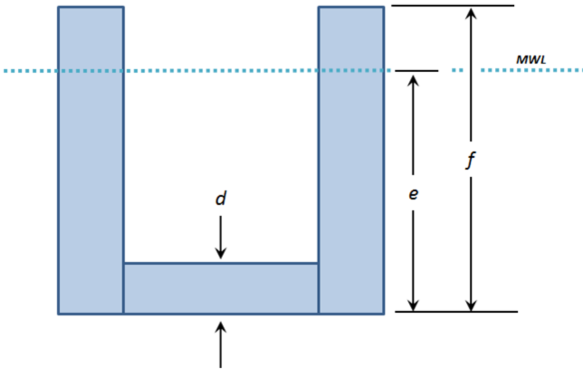
Design Process

Concept #1: Four-column Semi

- General Description
  - Four-column, square-symmetric semi-submersible unit with a ring pontoon configuration and a taut polyester mooring system.
  - The wind turbine is located centrally relative to the columns which provide buoyancy to support the turbine and sufficient water plane inertia to maintain stability.
  - Water ballast inside the pontoons and the bottom of the columns lower the platform to achieve its operational draft.
  - Primary hull dimensions:
    - a: pontoon spread
    - b: column width
    - c: pontoon width
    - d: pontoon height
    - e: operational draft
    - f: column height
  - Primary advantages:
    - Established hull type with proven reliability in many offshore applications
    - Feasibility of tow-out with fully installed topsides
  - Primary disadvantages:
    - May not be amenable for mass production



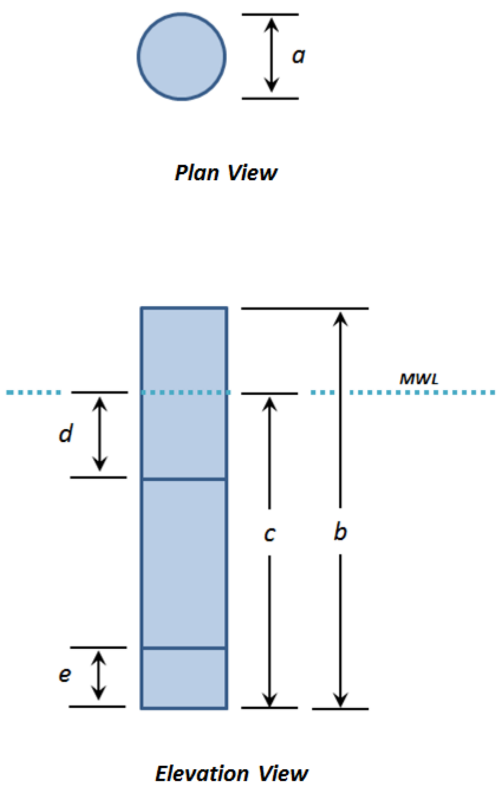
Plan View



Elevation View

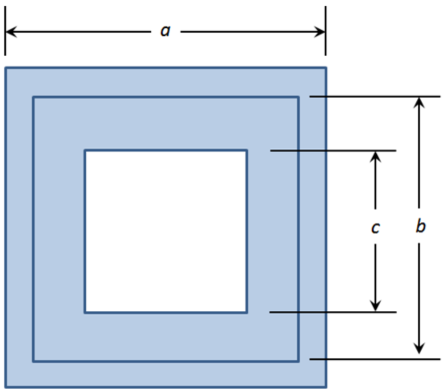
Concept #2: Classic Spar

- General Description
  - Traditional deep-draft spar buoy structure with a taut polyester mooring system.
  - The hard tank (located at the water's surface) is assumed to be comprised of six vertical compartments, where the bottommost compartment is available for variable water ballast and the others are void.
  - The soft tank (located at the bottom of the spar) includes a permanent ballasting section with material (iron ore) that weighs more than water, ensuring the center of gravity is located below the center of buoyancy.
  - Primary hull dimensions:
    - a: spar diameter
    - b: spar height
    - c: operational draft
    - d: hard tank draft
    - e: soft tank height
  - Primary advantages:
    - Established hull type with proven reliability in many offshore applications
    - Amenable to mass production
  - Primary disadvantage:
    - Not feasible to tow-out with fully installed topsides

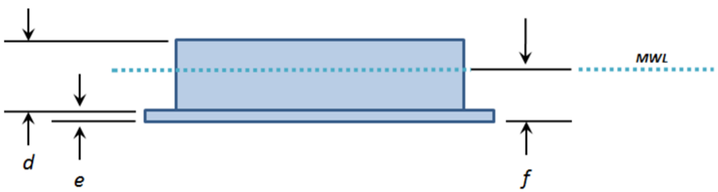


Concept #3: Ring Pontoon

- General Description
  - Square-symmetric ring pontoon configuration with a skirt extension (for heave damping) at the keel and a taut polyester mooring system.
  - The wind turbine is located centrally relative to the pontoons which provide buoyancy to support the turbine and sufficient water plane inertia to maintain stability.
  - Water ballast inside the pontoon lowers the platform to achieve its operational draft.
  - Primary hull dimensions:
    - a: skirt length
    - b: pontoon outer length
    - c: pontoon inner length
    - d: pontoon height above skirt
    - e: skirt thickness
    - f: operational draft
  - Primary advantage:
    - Feasibility of tow-out with fully installed topsides
  - Primary disadvantages:
    - No extensive field record of reliability
    - Developing favorable motion characteristics may be difficult



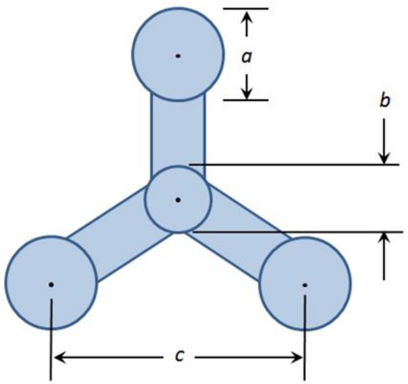
Plan View



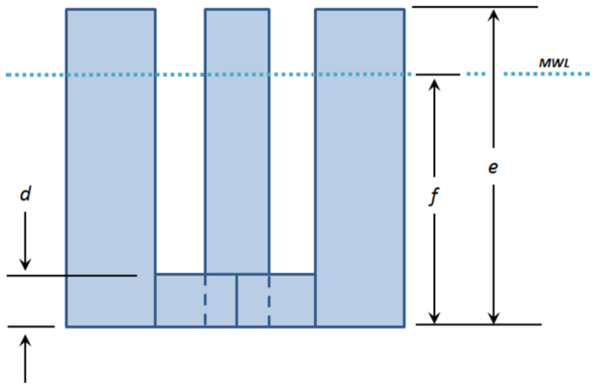
Elevation View

Concept #4: Compact Semi

- General Description:
  - Four-column semi-submersible unit with three lines of symmetry, a spoke-type pontoon configuration, and a taut polyester mooring system.
  - The wind turbine is located centrally relative to the columns which provide buoyancy to support the turbine and sufficient water plane inertia to maintain stability.
  - Water ballast inside the pontoons and the bottom of the columns lower the platform to achieve its operational draft.
  - Primary hull dimensions:
    - a: outer column diameter
    - b: inner column diameter
    - c: outer column spacing
    - d: pontoon height
    - e: column height
    - f: operational draft
  - Primary advantages:
    - Feasibility of tow-out with fully installed topsides
  - Primary disadvantages:
    - No extensive field record of reliability
    - Potential fatigue issues at pontoon / column connections
    - Triangular column geometry makes achieving damage stability requirements more difficult



Plan View

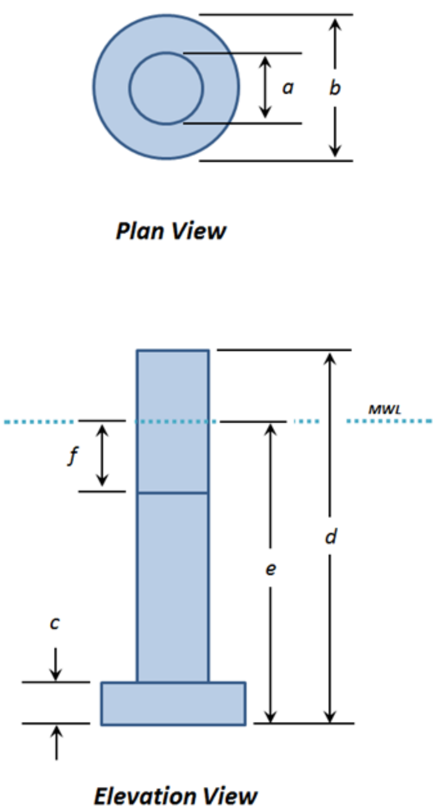


Elevation View

Concept #5: Advanced Spar

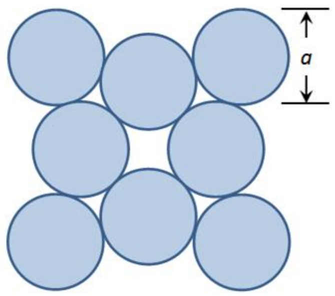
- General Description
  - Non-traditional deep-draft spar buoy structure with a cylindrical pontoon for its soft tank and taut polyester mooring system.
  - The hard tank is assumed to be comprised of six vertical compartments, where the bottommost compartment is available for variable water ballast and the others are void.
  - The soft tank includes a permanent ballasting section with material that weighs more than water, ensuring the center of gravity is located below the center of buoyancy.
  - Primary hull dimensions:
    - a: spar diameter
    - b: soft tank / pontoon diameter
    - c: soft tank / pontoon height
    - d: distance from keel to top of spar
    - e: operational draft
    - f: hard tank draft
  - Primary advantage:
    - Feasibility of tow-out with fully installed topsides
  - Primary disadvantages:
    - No extensive field record of reliability
    - Potential difficulties with topside assembly in dry dock

Advanced Spar

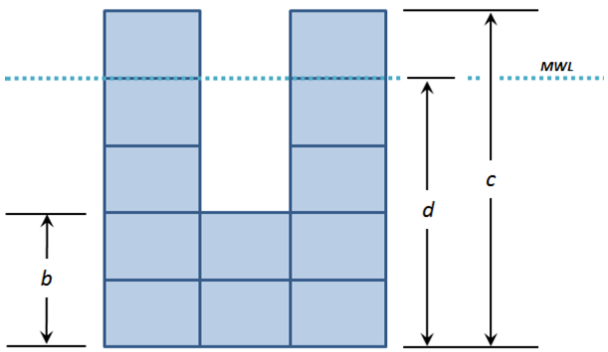


Concept #6: Multi-cellular TLP

- General Description
  - A square-symmetric hull structure with wire rope tendons. Pontoons and columns are comprised of cylindrical units called "cells" which are held together by structural steel shear connectors.
  - The wind turbine is located centrally relative to the columns which provide buoyancy to support the turbine and sufficient water plane inertia to maintain stability.
  - Water ballast inside the pontoons and the bottom of the columns lower the platform to achieve its operational draft.
  - Primary hull dimensions:
    - a: cell diameter
    - b: pontoon height
    - c: column height
    - d: operational draft
  - Primary advantages:
    - Feasibility of tow-out with fully installed topsides
    - Amenable to mass production
    - Excellent motion characteristics
  - Primary disadvantages:
    - No extensive field record of reliability
    - Potential fatigue issues with steel holding pontoons and columns together



Plan View



Elevation View

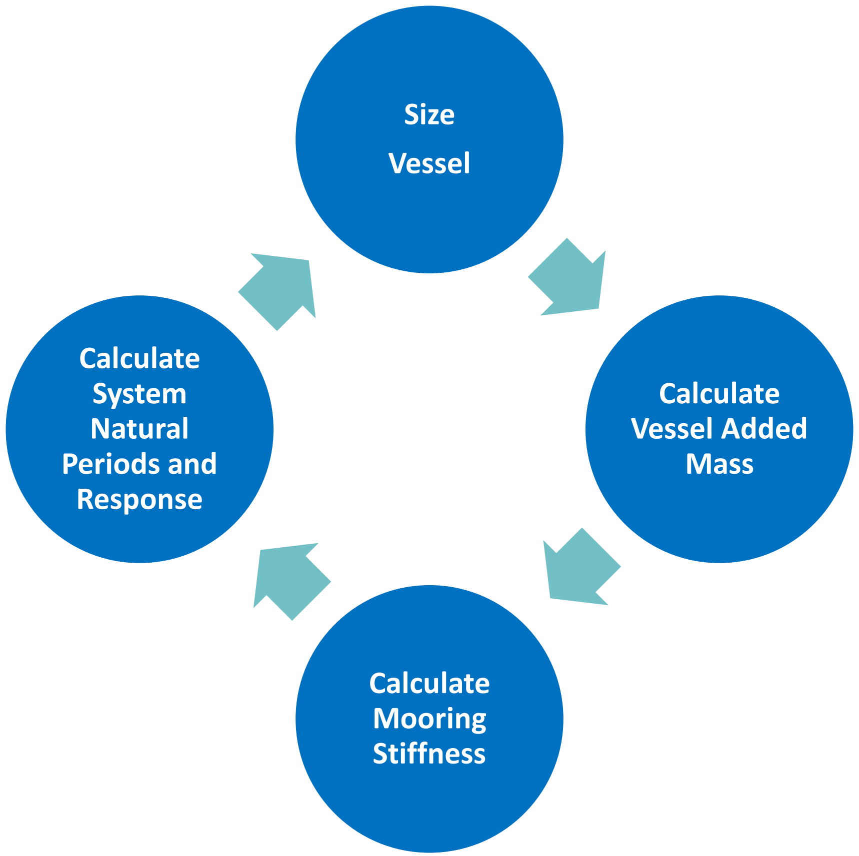
Mooring and Tendons

- Phase 1 Mooring Guidelines for Non-TLP Concepts
  - Taut polyester mooring system
  - Mooring arrangement is particular to each concept
  - Diameter of mooring line: 60 mm (2.36 inches)
  - Minimum breaking strength (estimated): 1,000 kN
  - Quasi-static axial stiffness: 15,000 kN
  - Target nominal tension in each line (10% MBS): 100 kN

- Phase 1 Tendon Guidelines for TLP Concept
  - Highly-tensioned spiral strand wire rope tendons
  - Diameter of tendon: 108 mm (4.5 inch)
  - Minimum breaking strength: 11,427 kN
  - Axial stiffness: 1,093,000 kN
  - Target nominal tension in each line: 3,000 kN

Design Process

Phase 1 Design Sequence



Phase 1 Design Sequence

- Step 1 of 4: Size Vessel
  - Provide Initial Sizing Parameters:
    - General Hull Dimensions
    - Operational Draft
    - Vertical Mooring Tension
    - Water Ballast
    - Freeboard
    - Payload
  - Calculate Displacement, Center of Buoyancy, and Metacenter
  - Estimate Lightship Weight
    - For preliminary sizing, use weight estimation rules published by Halkyard [1].
  - Center of Gravity, and Metacentric Height
  - Use Excel Solver Algorithm to Target Primary Vessel Attributes:
    - Minimize Lightship Weight (to reduce cost of steel)
    - Target Vessel GM (to ensure fundamental stability)
    - Target Tow Draft (not applicable to Classic Spar)

Compact Semi-Submersible

General Dimensions

Pontoon	Column-base pontoon spacing	*c*	30	*m*	98	*ft*
	Planview area of pontoons		**164**	m^2	1,764	ft^2
	Connecting pontoon height	*d*	6	*m*	20	*ft*
	Displaced volume of pontoons		**988**	m^3	34,886	ft^3
Column	Center column diameter	*b*	**7**	*m*	22	*ft*
	Outer column diameter	*a*	13	*m*	43	*ft*
	Column height	*e*	**15**	*m*	49	*ft*
	Water plane area		**444**	m^2	4,775	ft^2
	Displaced volume of columns		**4,449**	m^3	157,125	ft^3
	Draft	*f*	**10**	*m*	33	*ft*
Total Displaced Volume			**5,437**	m^3	192,010	ft^3
Draft		d_o	**10**	*m*	33	*ft*
Displacement		Δ_o	54,663	*kN*	**12,289**	*kips*
Distance from Keel to Center of Buoyancy		*KB*	**4.651**	*m*	15	*ft*
Distance from Center of Buoyancy to Metacenter		*BM*	**12**	*m*	40	*ft*
Distance from Keel to Metacenter		*KM = KB + BM*	**17**	*m*	55	*ft*

LIGHTSHIP		**33,111**	*kN*	7,444	*kips*
Mooring Tension		**270**	*kN*	61	*kips*
Deck Variable Load		**0**	*kN*	0	*kips*
Column Variable Load		**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)		**17,925**	*kN*	4,030	*kips*
Subtotal External Load, Variable Load, and Ballast		**18,195**	*kN*	4,090	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE		**51,306**	*kN*	11,534	*kips*
Distance from Keel to Center of Gravity	*KG*	**8.85**	*m*	29	*ft*
Distance from Center of Gravity to Metacenter	*GM = KM - KG*	**7.90**	*m*	26	*ft*
Displacement - Supported Weight (must equal zero)		**3,356**	*kN*	**755**	*kips*
Lightship weight (needs to be minimize)		**33,111**	*kN*	**7,444**	*kips*
Tow Draft		5.42	*m*	**17.79**	*ft*
Tow Draft - Halkyard Estimate		-0.13	*m*	**-0.41**	*ft*

Phase 1 Design Sequence

- Step 2 of 4: Calculate Vessel Added Mass
  - Closed-form solutions for determining added mass are available for only a few simple shapes. Thus, using WAMIT was decided to be the best way to determine the vessel added mass.
  - Calculation Procedure:
    - Generate PATRAN script based on sizing performed in Step 1
    - Use PATRAN to generate a finite element mesh of the immersed portion of the hull
    - Estimate mass matrix of the vessel
    - Submit finite element mesh and mass matrix to WAMIT to determine the vessel added mass at infinite wave period (quasi-static)
    - In addition to the added mass, WAMIT will calculate the vessel hydrostatic stiffness

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$# ***** CREATE NEW PATRAN DATA
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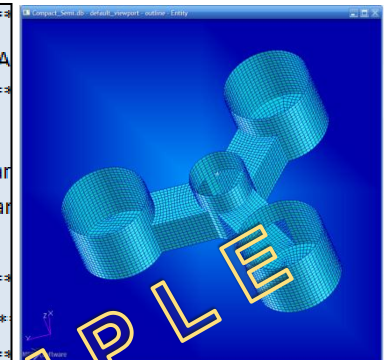
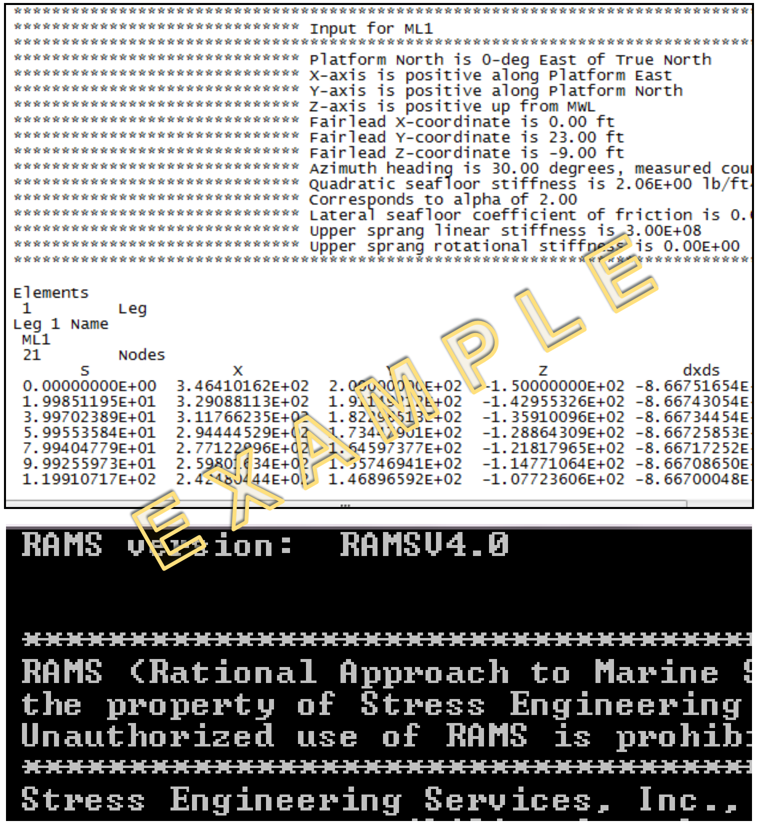


Component	Moments of Iner		
	I_{XX}	I_{YY}	I_{ZZ}
	kg-m^2	kg-m^2	kg-m^2
Pontoon 1	6.77E+06	9.22E+06	5.71E+06
Pontoon 2	1.05E+07	5.52E+06	5.71E+06
Pontoon 3	6.09E+06	8.54E+06	5.71E+06
Sub Total	2.34E+07	2.33E+07	1.71E+07
Center Column 1	5.13E+06	5.13E+06	1.03E+06
Outer Column 1	7.91E+07	1.86E+08	2.29E+08
Outer Column 2	2.39E+08	2.57E+07	2.29E+08
Outer Column 3	7.91E+07	1.86E+08	2.29E+08
Sub Total	4.03E+08	4.03E+08	6.89E+08
Deck Steel (basic structure)	1.02E+07	1.02E+07	1.14E+07

Phase 1 Design Sequence

- Step 3 of 4: Calculate Mooring Stiffness
  - Stress Engineering Services' proprietary software RAMS offers the fastest way to develop a mooring system model and evaluate its contribution to the global stiffness of the system.
  - Evaluation Procedure:
    - Determine key mooring parameters: number of lines, spread, component type and length, cross-section, axial stiffness, and pretension
    - Use key mooring parameters to generate a RAMS mooring model
    - Use RAMS to calculate the contribution of the mooring system to the tangent stiffness of the global system in its nominal configuration
    - Perform sensitivity check on the mooring stiffness by applying a static yaw moment equivalent to the maximum VAWT rotor torque and verify the resulting yaw displacement



Phase 1 Design Sequence

- Step 4 of 4: Calculate System Natural Periods
  - Evaluation Procedure:
    - Combine hull stiffness from WAMIT with mooring stiffness from RAMS to generate the stiffness of the global system
    - Combine vessel mass matrix from Excel with the vessel added mass from WAMIT to generate the mass matrix of the system
    - Using the system mass and stiffness matrices to calculate the system natural periods in surge, sway, heave, roll, pitch, and yaw
    - Compare system natural periods to periods of loads
      - Wave peak period: 10 seconds
      - VAWT harmonic loads: 4, 8, & 16 seconds
    - Use maximum overturning moment at cutout to estimate the associated vessel roll / pitch displacement.
    - Use maximum rotor torque to estimate associated yaw displacement
- Repeat Steps 1 through 4 as necessary to achieve desired system natural periods and vessel motion characteristics

Hull Data		
K_{33}	4.683E+06	N/m
K_{44}	7.436E+06	(N-m)/deg
K_{55}	7.436E+06	(N-m)/deg

(1)wrt MWL

(2)about MWL

Mooring Data		
Vertical Force	270	kN
K_{11}	1.592E+05	N/m
K_{22}	1.592E+05	N/m
K_{33}	2.726E+04	N/m
K_{44}	2.269E+05	(N-m)/deg
K_{55}	2.269E+05	(N-m)/deg
K_{66}	1.654E+06	(N-m)/deg

System Stiffness		
K_{11}	1.592E+05	N/m
K_{22}	1.592E+05	N/m
K_{33}	4.710E+06	N/m
K_{44}	7.663E+06	(N-m)/deg
K_{55}	7.662E+06	(N-m)/deg
K_{66}	1.654E+06	(N-m)/deg

System Mass/Inertia		
M_{11}	9.290[illegible]E+06	kg
M_{22}	9.2910E+06	kg
M_{33}	9.[illegible]013E+06	kg
I_{44}	1.9395E+09	$kg\text{-}m^2$
I_{55}	1.9724E+09	$kg\text{-}m^2$
I_{66}	1.9564E+09	$kg\text{-}m^2$

Rotational Mode	System deg	Limit deg	Ratio -
xxxRoll	22.8	10.0	2.3
xxxPitch	22.8	10.0	2.3
xxxYaw	4.4	20.0	0.2

"xxx" is defined by Sandia input (i.e. "static", "rms", "MPME", etc); recall that environment

System Natural Periods			Wave Tp		Aero1	
T_{11}	46	sec	10	0.2	16	0.3
T_{22}	46	sec	10	0.2	16	0.3
T_{33}	9	sec	10	1.1	16	1.8
T_{44}	19	sec	10	0.5	16	0.8
T_{55}	19	sec	10	0.5	16	0.8
T_{66}	23	sec	10	0.4	16	0.7

STRESS ENGINEERING SERVICES INC. an employee-owned company

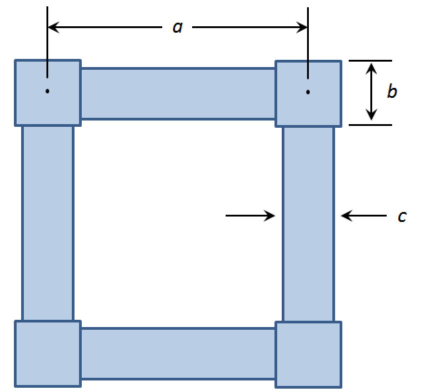
Concept #1: Four-column Semi

1st Design Pass

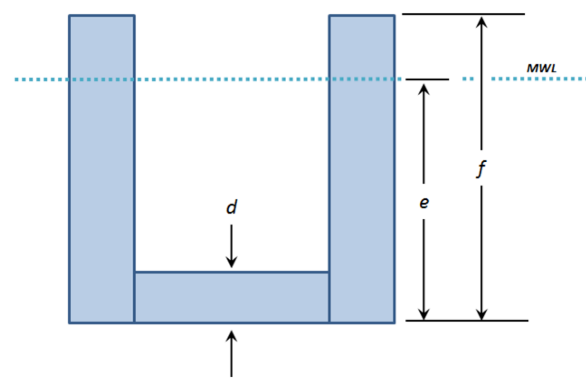
General Dimensions

Pontoon	Side Pontoon width	***c***	8	*m*	26	*ft*
	Side Pontoon height	***d***	5	*m*	16	*ft*
	Side Pontoon cross-section		**39**	m^2	423	ft^2
	Side Pontoon length		**18**	*m*	60	*ft*
	Side Pontoon lateral spread		**26**	*m*	87	*ft*
	End Pontoon width		**8**	*m*	26	*ft*
	End Pontoon height		**5**	*m*	16	*ft*
	End Pontoon cross-section		**39**	m^2	423	ft^2
	End Pontoon length		**18**	*m*	60	*ft*
	End Pontoon lateral spread		**26**	*m*	87	*ft*
	Pontoon center submergence (all)		**8**	*m*	25	*ft*
	Pontoon volume (total)		**2,897**	m^3	102,308	ft^3
Column	Column width	***b***	8	*m*	26	*ft*
	Column cross-section		**63**	m^2	682	ft^2
	Column submerged depth (draft)	***e***	10	*m*	33	*ft*
	Column longitudinal spread	***a***	26	*m*	87	*ft*
	Column lateral spread		**26**	*m*	87	*ft*
	Column height (wt top)	***f***	**15**	*m*	49	*ft*
	Water plane area		254	m^2	2,729	ft^2
	Immersed column volume		**2,550**	m^3	90,066	ft^3
Vessel Width at Keel			**34**	*m*	113	*ft*
Total Displaced Volume			**5,448**	m^3	192,374	ft^3

Draft	***e***	**10**	*m*	33	*ft*
Displacement	Δ_o	54,766	*kN*	**12,312**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**3.6845**	*m*	12	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**8.35**	*m*	27	*ft*
Distance from Keel to Metacenter	***KM = KB + BM***	**12**	*m*	39	*ft*



Plan View



Elevation View

STRESS ENGINEERING SERVICES INC.

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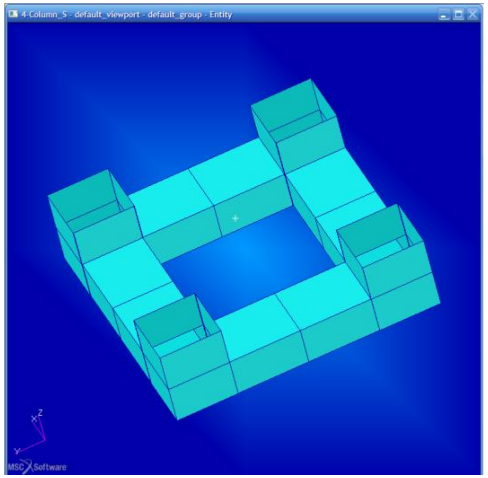
Concept #1: Four-column Semi

1st Design Pass

Hull Weight and Force Breakdown Groups

Pontoon Steel	6,826	*kN*	**1,535**	*kips*
Special Steel	**683**	*kN*	153	*kips*
Pontoon Outfit and Equipment	**1,024**	*kN*	230	*kips*
Pontoon Subtotal	**8,533**	*kN*	1,918	*kips*
Column Steel	8,996	*kN*	**2,022**	*kips*
Special Steel	**900**	*kN*	202	*kips*
Column Outfit and Equipment	**1,349**	*kN*	303	*kips*
Column Subtotal	**11,245**	*kN*	2,528	*kips*
Deck Steel (basic structure)	**5,580**	*kN*	1,254	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add. Deck Equipment & Outfit - Marine and Support	**0**	*kN*	0	*kips*
Add. Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**11,160**	*kN*	2,509	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**558**	*kN*	125	*kips*
Pontoon Fixed Ballast	**0**	*kN*	0	*kips*
LIGHTSHIP	**31,496**	*kN*	7,081	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)	23,000	*kN*	5,171	*kips*
Subtotal External Load, Variable Load, and Ballast	**23,270**	*kN*	5,231	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**54,766**	*kN*	12,312	*kips*

Distance from Keel to Center of Gravity	***KG***	**8.03**	*m*	26	*ft*
Distance from CG to Metacenter	***GM = KM - KG***	**4.00**	*m*	13	*ft*



PATRAN Model

Concept #1: Four-column Semi

1st Design Pass

- System Stiffness and Mass/Inertia Terms:

System Stiffness			System Mass/Inertia		
K_{11}	1.329E+05	N/m	M_{11}	9.1883E+06	kg
K_{22}	1.329E+05	N/m	M_{22}	9.1883E+06	kg
K_{33}	2.585E+06	N/m	M_{33}	1.3305E+07	kg
K_{44}	4.132E+06	(N-m)/deg	I_{44}	2.9460E+09	kg-m^2
K_{55}	4.132E+06	(N-m)/deg	I_{55}	2.9790E+09	kg-m^2
K_{66}	1.076E+06	(N-m)/deg	I_{66}	1.9471E+09	kg-m^2

- System Natural Periods and Maximum Motion Limits

System Natural Periods		
T_{11}	52	sec
T_{22}	52	sec
T_{33}	14	sec
T_{44}	22	sec
T_{55}	22	sec
T_{66}	35	sec

Rotational Mode	System deg
Roll	19.2
Pitch	19.2
Yaw	6.8

- Conclusion:
  - Heave natural period is too low. A period closer to 20 seconds or higher is more appropriate.
  - The roll/pitch periods may also need to be increased slightly.

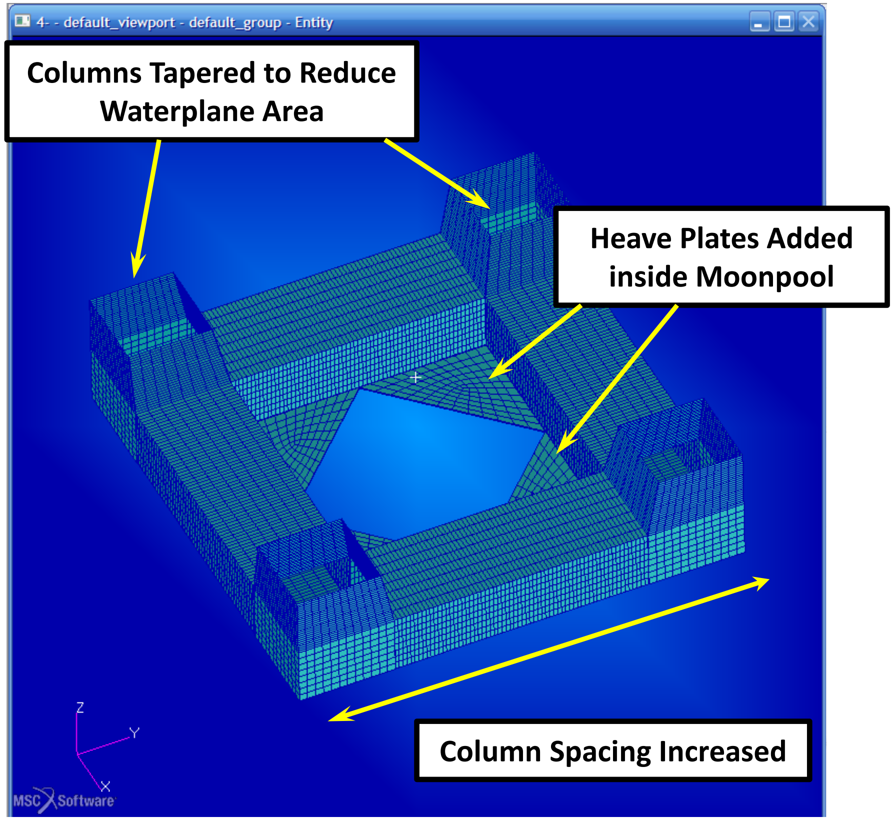
Note: System natural periods are estimated using the diagonal terms of the mass and stiffness matrices.

Vessel Sizing

Concept #1: Four-column Semi

2nd Design Pass

- To improve the natural period characteristics of the 4-column semi-submersible, the following changes were implemented:
  - Tapered Columns
    - The inner faces of all four columns were tapered by 1 m in both planform directions.
    - By reducing the waterplane area, the vessel's heave stiffness is also reduced.
    - Additionally, the taper slightly increases the heave added mass.
  - Heave Plates
    - Triangular heave plates were added to the four corners of the moonpool at the keel.
    - The additional heave added mass will increase the heave natural period.
  - Increased Column Spacing
    - The reduced waterplane area will result in increased roll/pitch motions.
    - Increasing the column spacing will the counter-act this effect.

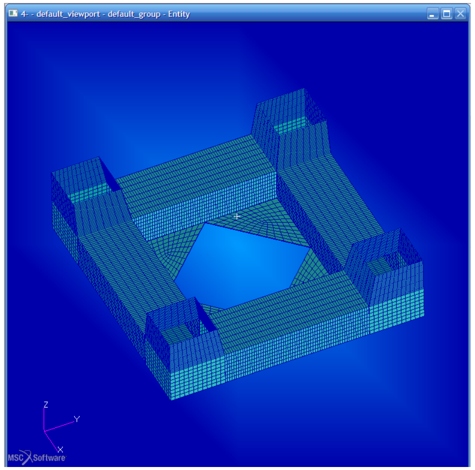


Concept #1: Four-column Semi

2nd Design Pass

General Dimensions

Pontoon	Side Pontoon width	*c*	8	*m*	26	*ft*
	Side Pontoon height	*d*	5	*m*	16	*ft*
	Side Pontoon cross-section		**39**	m^2	423	ft^2
	Side Pontoon length		**21**	*m*	69	*ft*
	Side Pontoon lateral spread		**29**	*m*	95	*ft*
	End Pontoon width		**8**	*m*	26	*ft*
	End Pontoon height		**5**	*m*	16	*ft*
	End Pontoon cross-section		**39**	m^2	423	ft^2
	End Pontoon length		**21**	*m*	69	*ft*
	End Pontoon lateral spread		**29**	*m*	95	*ft*
	Pontoon center submergence (all)		**8**	*m*	25	*ft*
	Pontoon volume (total)		**3,308**	m^3	116,811	ft^3
Column	Column width (at base)	*b*	8	*m*	26	*ft*
	Column cross-section (at base)		**63**	m^2	682	ft^2
	Column submerged depth (draft)	*e*	10	*m*	33	*ft*
	Column longitudinal spread	*a*	29	*m*	95	*ft*
	Column lateral spread		**29**	*m*	95	*ft*
	Column height (wt top)	*f*	15	*m*	49	*ft*
	Water plane area		254	m^2	2,729	ft^2
	Immersed column volume		**2,550**	m^3	90,066	ft^3
Vessel Width at Keel			**37**	*m*	121	*ft*
Total Displaced Volume			**5,858**	m^3	206,877	ft^3



PATRAN Model

Draft	*e*	**10** *m*	33	*ft*
Displacement	Δ_o	58,895 *kN*	**13,240**	*kips*
Distance from Keel to Center of Buoyancy	*KB*	**3.6014** *m*	12	*ft*
Distance from Center of Buoyancy to Metacenter	*BM*	**7.58** *m*	25	*ft*
Distance from Keel to Metacenter	*KM = KB + BM*	**11** *m*	37	*ft*

Vessel Sizing

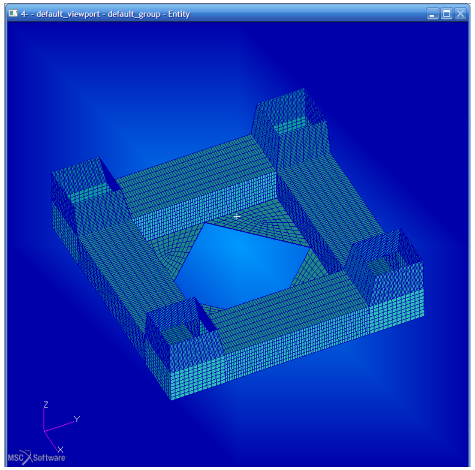
Concept #1: Four-column Semi

2nd Design Pass

Hull Weight and Force Breakdown Groups

Pontoon Steel	7,794	*kN*	**1,752**	*kips*
Special Steel	**779**	*kN*	175	*kips*
Pontoon Outfit and Equipment	**1,169**	*kN*	263	*kips*
Pontoon Subtotal	**9,742**	*kN*	2,190	*kips*
Column Steel	8,996	*kN*	**2,022**	*kips*
Special Steel	**900**	*kN*	202	*kips*
Column Outfit and Equipment	**1,349**	*kN*	303	*kips*
Column Subtotal	**11,245**	*kN*	2,528	*kips*
Deck Steel (basic structure)	**5,580**	*kN*	1,254	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Additional Deck Equipment and Outfit - Marine and Support	**0**	*kN*	0	*kips*
Additional Deck Equipment and Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**11,160**	*kN*	2,509	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**558**	*kN*	125	*kips*
Pontoon Fixed Ballast	**0**	*kN*	0	*kips*
LIGHTSHIP	**32,706**	*kN*	7,353	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)	**25,919**	*kN*	5,827	*kips*
Subtotal External Load, Variable Load, and Ballast	**26,189**	*kN*	5,888	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**58,895**	*kN*	13,240	*kips*

Distance from Keel to Center of Gravity	***KG***	**7.60**	*m*	25	*ft*
Distance from Center of Gravity to Metacenter	***GM = KM - KG***	**3.58**	*m*	12	*ft*



PATRAN Model

Concept #1: Four-column Semi

2nd Design Pass

- System Stiffness and Mass/Inertia Terms:

System Stiffness			System Mass/Inertia		
K_{11}	1.329E+05	N/m	M_{11}	9.8088E+06	kg
K_{22}	1.329E+05	N/m	M_{22}	9.7811E+06	kg
K_{33}	1.985E+06	N/m	M_{33}	1.8914E+07	kg
K_{44}	3.993E+06	(N-m)/deg	I_{44}	3.6351E+09	kg-m^2
K_{55}	3.995E+06	(N-m)/deg	I_{55}	3.6509E+09	kg-m^2
K_{66}	1.076E+06	(N-m)/deg	I_{66}	2.4362E+09	kg-m^2

- System Natural Periods and Maximum Motion Limits

System Natural Periods		
T_{11}	54	sec
T_{22}	54	sec
T_{33}	19	sec
T_{44}	25	sec
T_{55}	25	sec
T_{66}	40	sec

Rotational Mode	System deg
Roll	19.9
Pitch	19.8
Yaw	6.8

- Conclusions:
  - The remedies implemented have increased the heave natural period to 19 seconds.
  - The roll/pitch natural periods also increased to 25 seconds.
  - Similar remedies can be implemented to adjust characteristics of other vessel types.

Note: System natural periods are estimated using the diagonal terms of the mass and stiffness matrices.

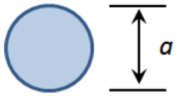
Concept #2: Classic Spar

General Dimensions

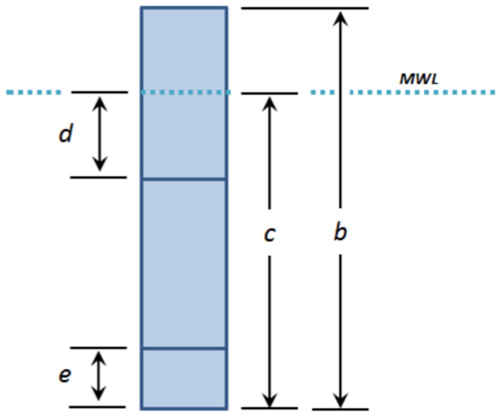
Column	Spar diameter	***a***	17	*m*	56	*ft*
	Spar height (wt top)	***b***	**75**	*m*	245	*ft*
	Spar draft	***c***	70	*m*	229	*ft*
	Hard tank draft	***d***	20	*m*	66	*ft*
	Height of soft tank	***e***	**3**	*m*	10	*ft*
	Water plane area		**232**	m^2	2,502	ft^2

Volumes	Hard tank (void)	**3,694**	m^3	130,455	ft^3
	Hard tank (variable)	**971**	m^3	34,300	ft^3
	Mid-section	**10,850**	m^3	383,162	ft^3
	Soft tank	**697**	m^3	24,628	ft^3
	Fixed ballast	--	m^3	--	ft^3
	Total displaced volume	**16,213**	m^3	572,545	ft^3

Draft	***c***	**70**	*m*	229	*ft*
Displacement	Δ_o	162,996	*kN*	**36,643**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**35**	*m*	114	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**0.265**	*m*	1	*ft*
Distance from Keel to Metacenter	***KM = KB + BM***	**35**	*m*	115	*ft*



Plan View



Elevation View

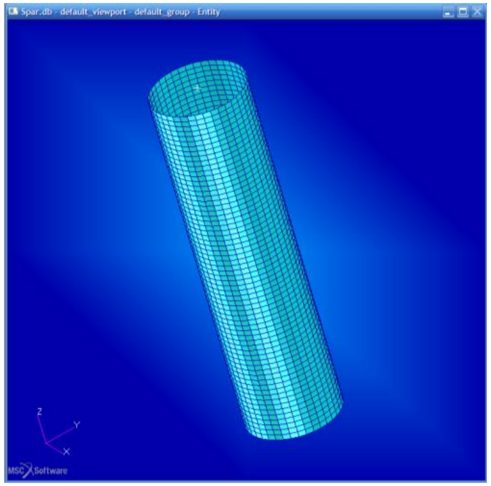
Vessel Sizing

Concept #2: Classic Spar

Hull Weight and Force Breakdown Groups

Hard Tank Steel	**7,311**	*kN*	1,644	*kips*
Mid-section Steel	**9,899**	*kN*	2,225	*kips*
Soft Tank Steel	**1,273**	*kN*	286	*kips*
Spar Hull Steel Subtotal	**18,482**	*kN*	4,155	*kips*
Special Steel	**1,848**	*kN*	416	*kips*
Spar Hull Outfit and Equipment	**2,772**	*kN*	623	*kips*
Spar Hull Subtotal	**23,103**	*kN*	5,194	*kips*
Deck Steel (basic structure)	7,842	*kN*	**1,763**	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add. Deck Equipment & Outfit - Marine and Support	**0**	*kN*	0	*kips*
Add. Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**13,422**	*kN*	3,017	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**784**	*kN*	176	*kips*
Hull Fixed Ballast	**10,738**	*kN*	2,414	*kips*
LIGHTSHIP	**48,047**	*kN*	10,801	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (hard tank)	**2,000**	*kN*	450	*kips*
Entrained Water (mid-section)	**109,103**	*kN*	24,527	*kips*
Entrained Water (soft tank)	**3,576**	*kN*	804	*kips*
Subtotal External Load, Variable Load, Ballast, Entrained Water	**114,949**	*kN*	25,841	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**162,996**	*kN*	36,643	*kips*

Distance from Keel to Center of Gravity	***KG***	**31.14**	*m*	102	*ft*
Distance from Center of Gravity to Metacenter	***GM = KM - KG***	**4.00**	*m*	13	*ft*



PATRAN Model

Concept #2: Classic Spar

- System Stiffness and Mass/Inertia Terms:

System Stiffness			System Mass/Inertia		
K_{11}	1.348E+05	N/m	M_{11}	3.0605E+07	kg
K_{22}	1.348E+05	N/m	M_{22}	3.0605E+07	kg
K_{33}	2.327E+06	N/m	M_{33}	1.7914E+07	kg
K_{44}	1.181E+07	(N-m)/deg	I_{44}	5.2104E+10	kg-m^2
K_{55}	1.181E+07	(N-m)/deg	I_{55}	5.2137E+10	kg-m^2
K_{66}	8.189E+05	(N-m)/deg	I_{66}	6.5356E+08	kg-m^2

- System Natural Periods and Maximum Motion Limits

System Natural Periods		
T_{11}	95	sec
T_{22}	95	sec
T_{33}	17	sec
T_{44}	55	sec
T_{55}	55	sec
T_{66}	23	sec

Rotational Mode	System deg
Roll	6.7
Pitch	6.7
Yaw	8.9

- Conclusions:
  - The heave natural period should be increased to at least 20 seconds.
  - The addition of a heave plate at the keel and a taper at the waterplane will cause the heave natural period to increase above 20 seconds.

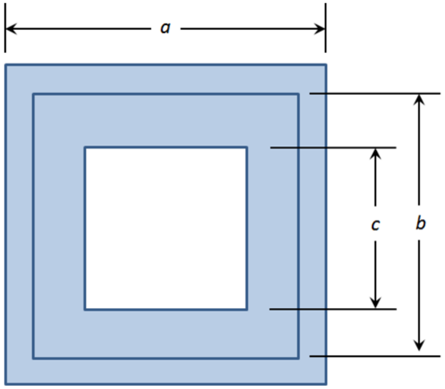
Note: System natural periods are estimated using the diagonal terms of the mass and stiffness matrices.

Concept #3: Ring Pontoon

General Dimensions

Pontoon	Pontoon length (outer)	***b***	**27**	*m*	90	*ft*
	Pontoon length (inner)	***c***	**10**	*m*	33	*ft*
	Pontoon height above skirt	***d***	**10**	*m*	33	*ft*
	Draft	***f***	**6**	*m*	20	*ft*
	Pontoon displaced volume		**3,890**	m^3	137,385	ft^3
Skirt	Skirt length	***a***	**44**	*m*	143	*ft*
	Skirt thickness	***e***	**1**	*m*	3	*ft*
	Skirt displaced volume		**1,148**	m^3	40,528	ft^3
Total Displaced Volume			**5,038**	m^3	177,913	ft^3

Draft	***f***	6	*m*	20	*ft*
Displacement	Δ_o	50,649	*kN*	**11,386**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**2.4**	*m*	8	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**9**	*m*	30	*ft*
Distance from Keel to Metacenter	***KM = KB + BM***	**12**	*m*	38	*ft*



Plan View

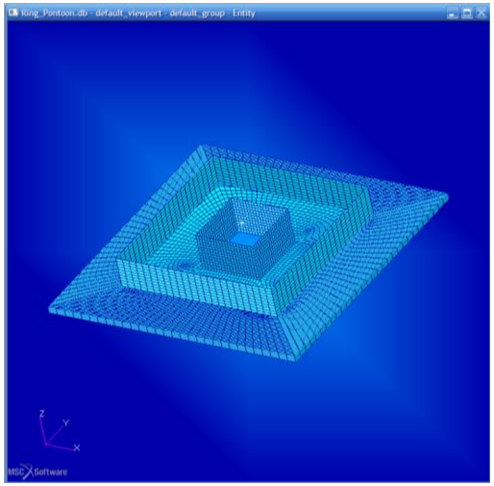
Elevation View

Concept #3: Ring Pontoon

Hull Weight and Force Breakdown Groups

Pontoon Steel	16,856	*kN*	**3,789**	*kips*
Special Steel	**1,686**	*kN*	379	*kips*
Pontoon Outfit and Equipment	**2,528**	*kN*	568	*kips*
Pontoon Subtotal	**21,070**	*kN*	4,737	*kips*
Skirt Steel	2,704	*kN*	**608**	*kips*
Special Steel	**270**	*kN*	61	*kips*
Skirt Outfit and Equipment	**406**	*kN*	91	*kips*
Skirt Subtotal	**3,380**	*kN*	760	*kips*
Deck Steel (basic structure)	**2,790**	*kN*	627	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add. Deck Equipment & Outfit - Marine and Support	**0**	*kN*	0	*kips*
Add. Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**8,370**	*kN*	1,882	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**279**	*kN*	63	*kips*
Pontoon Fixed Ballast	**0**	*kN*	0	*kips*
LIGHTSHIP	**33,099**	*kN*	7,441	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)	17,280	*kN*	3,885	*kips*
Subtotal External Load, Variable Load, and Ballast	**17,550**	*kN*	3,945	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**50,649**	*kN*	11,386	*kips*

Distance from Keel to Center of Gravity	***KG***	**7.50**	*m*	25	*ft*
Distance from Center of Gravity to Metacenter	***GM = KM - KG***	**4.14**	*m*	14	*ft*



PATRAN Model

Concept #3: Ring Pontoon

- System Stiffness and Mass/Inertia Terms:

System Stiffness			System Mass/Inertia		
K_{11}	1.329E+05	N/m	M_{11}	8.7300E+06	kg
K_{22}	1.329E+05	N/m	M_{22}	8.7300E+06	kg
K_{33}	6.599E+06	N/m	M_{33}	3.3648E+07	kg
K_{44}	3.977E+06	(N-m)/deg	I_{44}	5.6784E+09	kg-m^2
K_{55}	3.977E+06	(N-m)/deg	I_{55}	5.7114E+09	kg-m^2
K_{66}	1.076E+06	(N-m)/deg	I_{66}	9.2874E+08	kg-m^2

- System Natural Periods and Maximum Motion Limits

System Natural Periods		
T_{11}	51	sec
T_{22}	51	sec
T_{33}	14	sec
T_{44}	31	sec
T_{55}	31	sec
T_{66}	24	sec

Rotational Mode	System deg
Roll	19.9
Pitch	19.9
Yaw	6.8

- Conclusions:
  - The heave natural period should be increased to at least 20 seconds.
  - Extending the skirt may help; however, it is already considerably large.

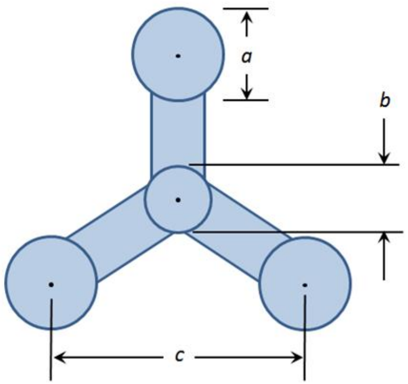
Note: System natural periods are estimated using the diagonal terms of the mass and stiffness matrices.

Concept #4: Compact Semi

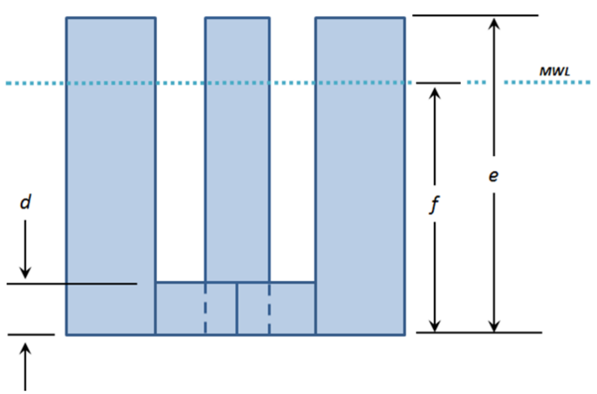
General Dimensions

Pontoon	Column-base pontoon spacing	*c*	25	*m*	83	*ft*
	Planview area of pontoons		**105**	m^2	1,132	ft^2
	Connecting pontoon height	*d*	7	*m*	22	*ft*
	Displaced volume of pontoons		**698**	m^3	24,664	ft^3
Column	Center column diameter	*b*	**7**	*m*	23	*ft*
	Outer column diameter	*a*	12	*m*	39	*ft*
	Column height	*e*	**16**	*m*	51	*ft*
	Water plane area		**379**	m^2	4,075	ft^2
	Displaced volume of columns		**4,028**	m^3	142,226	ft^3
	Draft	*f*	**11**	*m*	35	*ft*
Total Displaced Volume			**4,726**	m^3	166,890	ft^3

Draft	d_o	**11**	*m*	35	*ft*
Displacement	Δ_o	47,511	*kN*	**10,681**	*kips*
Distance from Keel to Center of Buoyancy	*KB*	**5.024**	*m*	16	*ft*
Distance from CB to Metacenter	*BM*	**8**	*m*	27	*ft*
Distance from Keel to Metacenter	*KM = KB + BM*	**13**	*m*	44	*ft*



Plan View

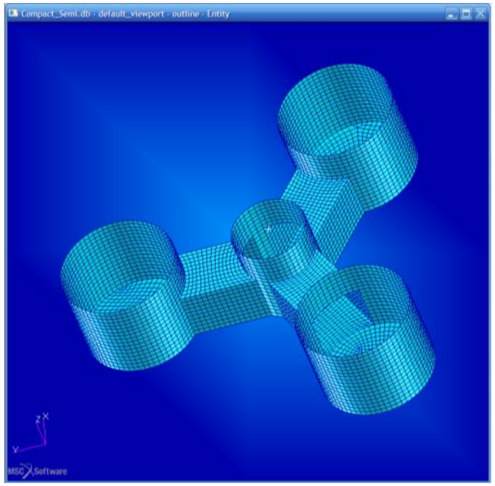


Elevation View

Concept #4: Compact Semi

Hull Weight and Force Breakdown Groups

Pontoon Steel	1,646 *kN*	**370** *kips*
Special Steel	**165** *kN*	37 *kips*
Pontoon Outfit and Equipment	**247** *kN*	55 *kips*
Pontoon Subtotal	**2,057** *kN*	462 *kips*
Center Column Steel	1,421 *kN*	**319** *kips*
Special Steel	**426** *kN*	96 *kips*
Column Outfit and Equipment	**213** *kN*	48 *kips*
Center Column Subtotal	**2,060** *kN*	463 *kips*
Outer Columns Steel	12,529 *kN*	**2,817** *kips*
Special Steel	3,759 *kN*	845 *kips*
Column Outfit and Equipment	1,879 *kN*	422 *kips*
Outer Column Subtotal	18,167 *kN*	4,084 *kips*
Deck Steel (basic structure)	**1,674** *kN*	376 *kips*
Deck Steel (deck houses)	**0** *kN*	0 *kips*
Special Steel	**0** *kN*	0 *kips*
Rotor	**2,166** *kN*	487 *kips*
Drivetrain	**2,923** *kN*	657 *kips*
Add. Deck Equipment & Outfit - Marine and Support	**0** *kN*	0 *kips*
Add. Deck Equipment & Outfit - Mission Systems	**491** *kN*	110 *kips*
Topsides Subtotal	**7,254** *kN*	1,631 *kips*
Other Hull Weight	**0** ***kN***	**0** ***kips***
Deck Reserve/Margin	**167** ***kN***	**38** ***kips***
Pontoon Fixed Ballast	**0** ***kN***	**0** ***kips***
LIGHTSHIP	**29,705** ***kN***	**6,678** ***kips***
Mooring Tension	**270** *kN*	61 *kips*
Deck Variable Load	**0** *kN*	0 *kips*
Column Variable Load	**0** *kN*	0 *kips*
Water Ballast (pontoon/column)	**17,536** *kN*	3,942 *kips*
Subtotal External Load, Variable Load, and Ballast	**17,806** *kN*	4,003 *kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**47,511** *kN*	10,681 *kips*
Distance from Keel to Center of Gravity ***KG***	**9.36** *m*	31 *ft*
Distance from Center of Gravity to Metacenter ***GM = KM - KG***	**4.00** *m*	13 *ft*



PATRAN Model

Concept #4: Compact Semi

- System Stiffness and Mass/Inertia Terms:

System Stiffness			System Mass/Inertia		
K_{11}	1.592E+05	N/m	M_{11}	8.5581E+06	kg
K_{22}	1.592E+05	N/m	M_{22}	8.5582E+06	kg
K_{33}	3.826E+06	N/m	M_{33}	7.9592E+06	kg
K_{44}	3.485E+06	(N-m)/deg	I_{44}	1.7936E+09	kg-m^2
K_{55}	3.485E+06	(N-m)/deg	I_{55}	1.8266E+09	kg-m^2
K_{66}	1.654E+06	(N-m)/deg	I_{66}	1.3048E+09	kg-m^2

- System Natural Periods and Maximum Motion Limits

System Natural Periods		
T_{11}	46	sec
T_{22}	46	sec
T_{33}	9	sec
T_{44}	19	sec
T_{55}	19	sec
T_{66}	23	sec

Rotational Mode	System deg
Roll	22.8
Pitch	22.8
Yaw	4.4

- Conclusions:
  - The heave natural period is adversely affected by the minimal planview area of the pontoons.
  - Remediation methods like tapering the columns and adding heave plates will help.

Note: System natural periods are estimated using the diagonal terms of the mass and stiffness matrices.

Concept #5: Advanced Spar

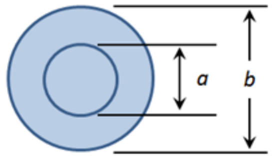
General Dimensions

Column	Spar diameter	***a***	**17**	*m*	56	*ft*
	Spar submerged depth		**44**	*m*	144	*ft*
	Spar height (wt top)	***d***	**55**	*m*	180	*ft*
	Hard tank draft	***f***	**20**	*m*	66	*ft*
	Water plane area		**232**	m^2	2,502	ft^2
Pontoon	Pontoon diameter	***b***	**32**	*m*	105	*ft*
	Pontoon height	***c***	**6**	*m*	21	*ft*
	Pontoon area		**804**	m^2	8,657	ft^2

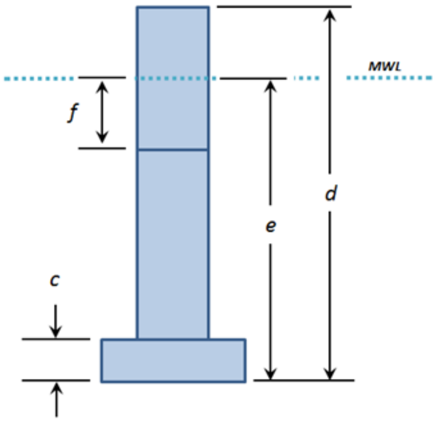
Volumes	Hard tank (void)	**3,694**	m^3	130,455	ft^3
	Hard tank (variable)	**971**	m^3	34,300	ft^3
	Mid-section	**5,504**	m^3	194,357	ft^3
	Soft tank (Pontoon)	**5,031**	m^3	177,648	ft^3
	Fixed ballast	--	m^3	--	ft^3
	Total displaced volume	**15,200**	m^3	536,760	ft^3

Draft	***e***	**50**	*m*	164	*ft*
Displacement	Δ_o	152,808	*kN*	**34,353**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**19.9**	*m*	65	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**0.283**	*m*	1	*ft*
Distance from Keel to Metacenter	***KM = KB + BM***	**20**	*m*	66	*ft*

Advanced Spar



Plan View



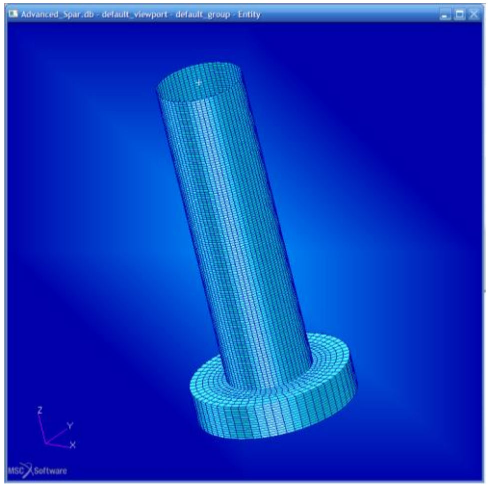
Elevation View

Concept #5: Advanced Spar

Hull Weight and Force Breakdown Groups

Hard Tank Steel	**7,311**	*kN*	1,644	*kips*
Mid-section Steel	**5,021**	*kN*	1,129	*kips*
Pontoon/Soft Tank Steel	**4,935**	*kN*	1,109	*kips*
Spar Hull Steel Subtotal	**17,267**	*kN*	3,882	*kips*
Special Steel	**1,727**	*kN*	388	*kips*
Spar Hull Outfit and Equipment	**2,590**	*kN*	582	*kips*
Spar Hull Subtotal	**21,584**	*kN*	4,852	*kips*
Deck Steel (basic structure)	7,842	*kN*	**1,763**	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add. Deck Equipment & Outfit - Marine and Support	**0**	*kN*	0	*kips*
Add. Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**13,422**	*kN*	3,017	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**784**	*kN*	176	*kips*
Hull Fixed Ballast	**10,738**	*kN*	2,414	*kips*
LIGHTSHIP	**46,528**	*kN*	10,460	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (column)	**3,521**	*kN*	792	*kips*
Entrained Water (mid-section)	**55,342**	*kN*	12,441	*kips*
Entrained Water (soft tank)	**47,147**	*kN*	10,599	*kips*
Subtotal External Load, Variable Load, and Ballast	**106,280**	*kN*	852	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**152,808**	*kN*	11,312	*kips*

Distance from Keel to Center of Gravity	***KG***	**17.66**	*m*	58	*ft*
Distance from Center of Gravity to Metacenter	***GM = KM - KG***	**2.48**	*m*	8	*ft*



PATRAN Model

Concept #5: Advanced Spar

- System Stiffness and Mass/Inertia Terms:

System Stiffness			System Mass/Inertia		
K_{11}	1.380E+05	N/m	M_{11}	3.2512E+07	kg
K_{22}	1.380E+05	N/m	M_{22}	3.2512E+07	kg
K_{33}	2.362E+06	N/m	M_{33}	2.6111E+07	kg
K_{44}	9.115E+06	(N-m)/deg	I_{44}	5.2750E+10	kg-m^2
K_{55}	9.115E+06	(N-m)/deg	I_{55}	5.2783E+10	kg-m^2
K_{66}	1.384E+06	(N-m)/deg	I_{66}	6.1514E+08	kg-m^2

- System Natural Periods and Maximum Motion Limits

System Natural Periods		
T_{11}	96	sec
T_{22}	96	sec
T_{33}	21	sec
T_{44}	63	sec
T_{55}	63	sec
T_{66}	17	sec

Rotational Mode	System deg
Roll	8.7
Pitch	8.7
Yaw	5.3

- Conclusions:
  - The heave natural period is above 20 seconds. This is because of the pontoon at the keel.

Note: System natural periods are estimated using the diagonal terms of the mass and stiffness matrices.

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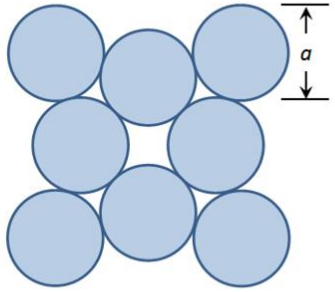
Concept #6: Multi-cellular TLP

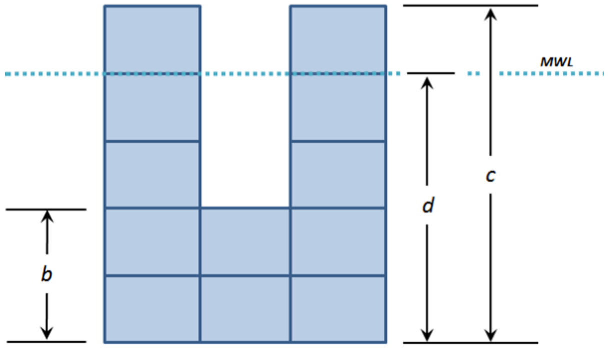
General Dimensions

Pontoon	Pontoon Cell diameter		**12**	*m*	38	*ft*
	Pontoon Cell height		**1**	*m*	3	*ft*
	Pontoon Cell cross-section		**105.8**	m^2	1,139	ft^2
	Number of Pontoon Cells in Single Stack		**5**	--	5	--
	Pontoon Height	***b***	**4.86**	*m*	16	*ft*
	Displaced volume of pontoons		**2,058**	m^3	72,675	ft^3
Column	Column Cell diameter	***a***	**12**	*m*	38	*ft*
	Column Cell height		**1**	*m*	3	*ft*
	Column Cell cross-section		**106**	m^2	1,139	ft^2
	Column height	***c***	**20**	*m*	65	*ft*
	Displaced volume of columns		**4,116**	m^3	145,351	ft^3
	Water plane area		**423**	m^2	4,555	ft^2
	Draft	***d***	**10**	*m*	32	*ft*
Total Displaced Volume			**6,174**	m^3	218,026	ft^3

Draft	***d***	10	*m*	32	*ft*
Displacement	Δ_o	62,069	*kN*	**13,954**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	4	*m*	13	*ft*
Distance from CB to Metacenter	***BM***	9	*m*	30	*ft*
Distance from Keel to Metacenter	***KM = KB + BM***	13	*m*	43	*ft*



Plan View



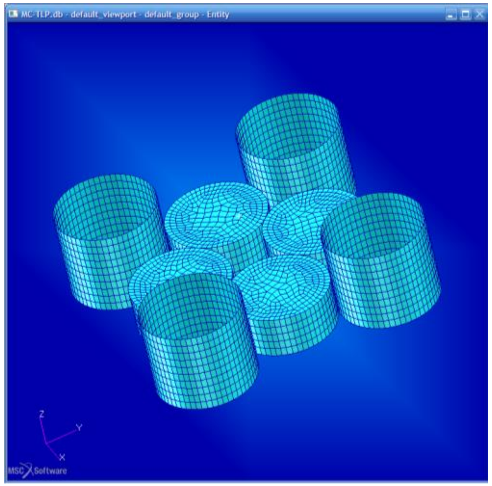
Elevation View

Concept #6: Multi-cellular TLP

Hull Weight and Force Breakdown Groups

Pontoon Steel	4,849	*kN*	**1,090**	*kips*
Special Steel	**485**	*kN*	109	*kips*
Pontoon Outfit and Equipment	**727**	*kN*	164	*kips*
Pontoon Subtotal	**6,061**	*kN*	1,363	*kips*
Column Steel	19,669	*kN*	**4,422**	*kips*
Special Steel	**1,967**	*kN*	442	*kips*
Column Outfit and Equipment	**2,950**	*kN*	663	*kips*
Column Subtotal	**24,586**	*kN*	5,527	*kips*
Deck Steel (basic structure)	**1,674**	*kN*	376	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add. Deck Equipment & Outfit - Marine and Support	**0**	*kN*	0	*kips*
Add. Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**7,254**	*kN*	1,631	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**167**	*kN*	38	*kips*
Pontoon Fixed Ballast	**0**	*kN*	0	*kips*
LIGHTSHIP	**38,069**	*kN*	8,558	*kips*
Mooring Tension	**24,000**	*kN*	5,395	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)	**0**	*kN*	0	*kips*
Subtotal External Load, Variable Load, and Ballast	**24,000**	*kN*	5,395	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**62,069**	*kN*	13,954	*kips*

Distance from Keel to Center of Gravity	***KG***	**8.61**	*m*	28	*ft*
Distance from CG to Metacenter	***GM = KM - KG***	**4.63**	*m*	15	*ft*



PATRAN Model

Concept #6: Multi-cellular TLP

- System Stiffness and Mass/Inertia Terms:

System Stiffness			System Mass/Inertia		
K_{11}	1.623E+05	N/m	M_{11}	7.3879E+06	kg
K_{22}	1.623E+05	N/m	M_{22}	7.3879E+06	kg
K_{33}	7.135E+07	N/m	M_{33}	1.3414E+07	kg
K_{44}	2.340E+08	(N-m)/deg	I_{44}	2.3365E+09	kg-m^2
K_{55}	2.340E+08	(N-m)/deg	I_{55}	2.3695E+09	kg-m^2
K_{66}	1.118E+06	(N-m)/deg	I_{66}	1.3740E+09	kg-m^2

- System Natural Periods and Maximum Motion Limits

System Natural Periods		
T_{11}	42	sec
T_{22}	42	sec
T_{33}	3	sec
T_{44}	3	sec
T_{55}	3	sec
T_{66}	29	sec

Rotational Mode	System deg
Roll	0.3
Pitch	0.3
Yaw	6.5

- Conclusions:
  - The spiral wire rope tendons effectively minimize the roll/pitch motions.

Note: System natural periods are estimated using the diagonal terms of the mass and stiffness matrices.

Basis of Phase 1 Cost Estimate

Screening Study of Potential Hull Forms

- Qualitative Selection of Representative Platforms
- Spreadsheet Design of Six Platforms for Specific Site
- Application of Historical Weight Density Factors
- Hydrostatics
- Stability
- Natural Periods

Aspects Included in Cost Estimate

Hull and Mooring Design and Construction

- Construction of Hull and Turbine Support Structures
- Procurement and Fabrication of Mooring System
- Tow Out of Floating Platform and Connection to Moorings

Aspects not Covered by Cost Estimate

- Pre-Construction Activities
  - Permitting
  - Selection of Fabrication Yard - Dry Dock Assumed
  - Seafloor Geo-Hazard and Geotechnical Survey
  - Determination of Fabrication Method –Crane Requirements
  - Preparation of Dry Dock and Towing Channel
- Hook-up and Commissioning of Turbine System
- Efficiency from Mass Production of 100 VAWT Systems
- Inflation
- Available Infrastructure or lack thereof

Aspects Included in Cost Estimate

Construction of Hull and Turbine Support Structures

- Materials-Bulks and Equipment
- Fabrication-Labor and Equipment
- Project Management, Overhead and Profit
- Engineering
- Certification

Aspects Included in Cost Estimate

Procurement and Fabrication of Mooring System

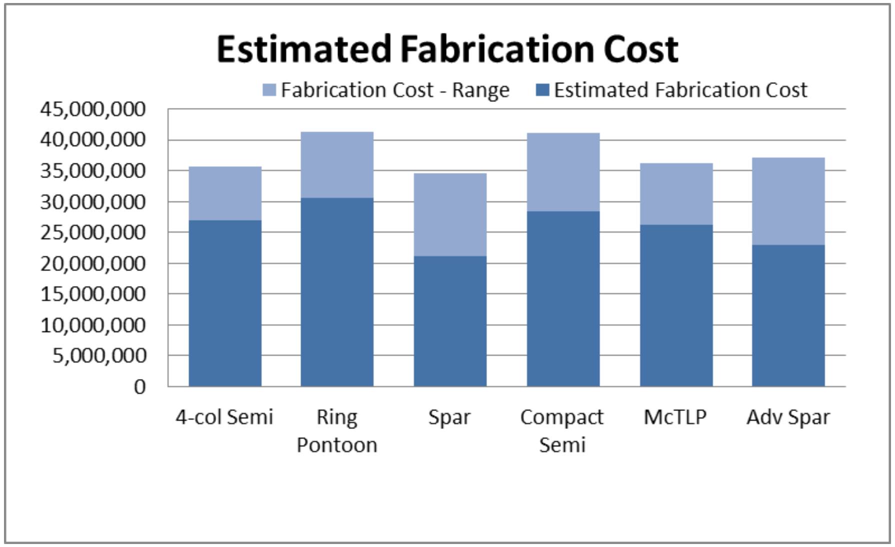
- Procurement of Mooring Lines-Polyester Rope, Wire Rope, Chain
- Procurement of Mooring Line Connectors-H-Links, Shackles, Ball Grabs
- Materials & Fabrication of Anchor Piles

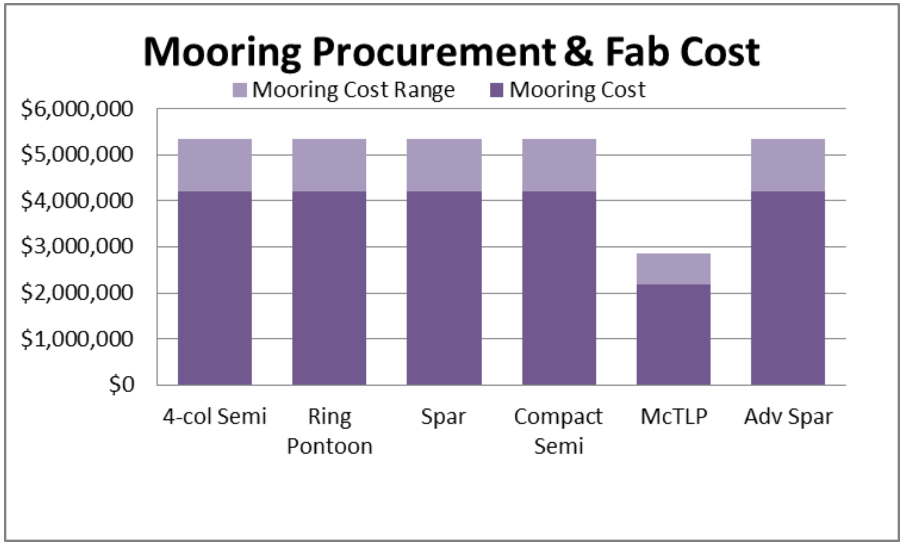
Aspects Included in Cost Estimate

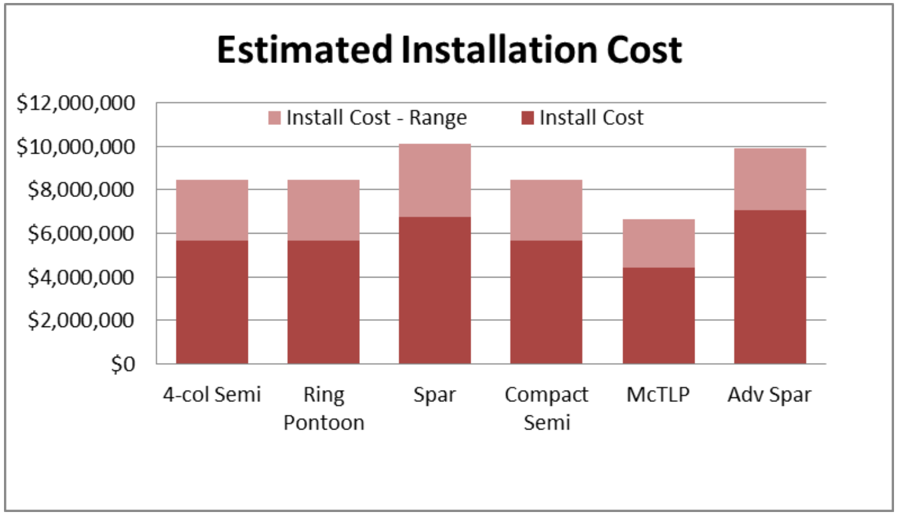
Tow Out of Floating Platform and Connection to Moorings

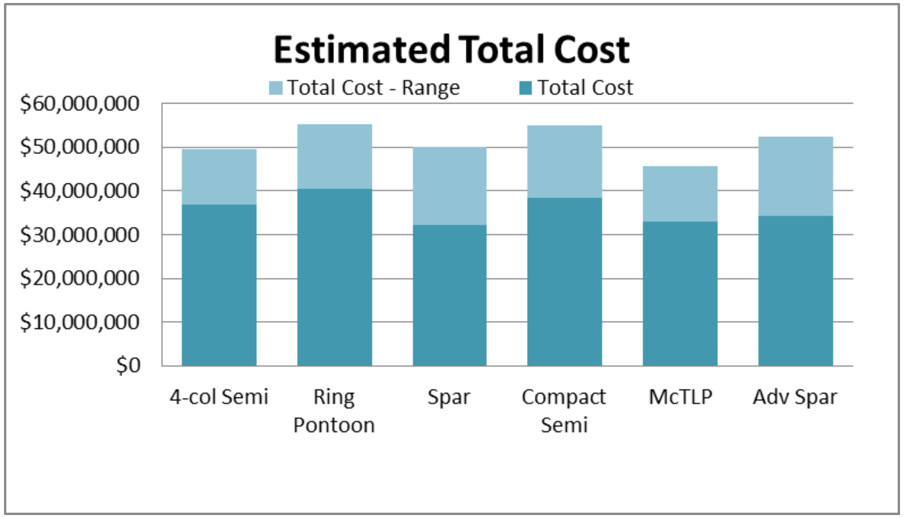
- Installation of Anchor Piles and Pre-Lay of Mooring Lines
- Tow of Floating Platform to Site with VAWT Installed
- Connection of Platform to Mooring Lines
- Connection of Subsea Transmission Cable
- Ballasting of Platform to Operating Draft
- Removal of Installation Equipment
- Start-Up of VAWT

Phase 1 Costs

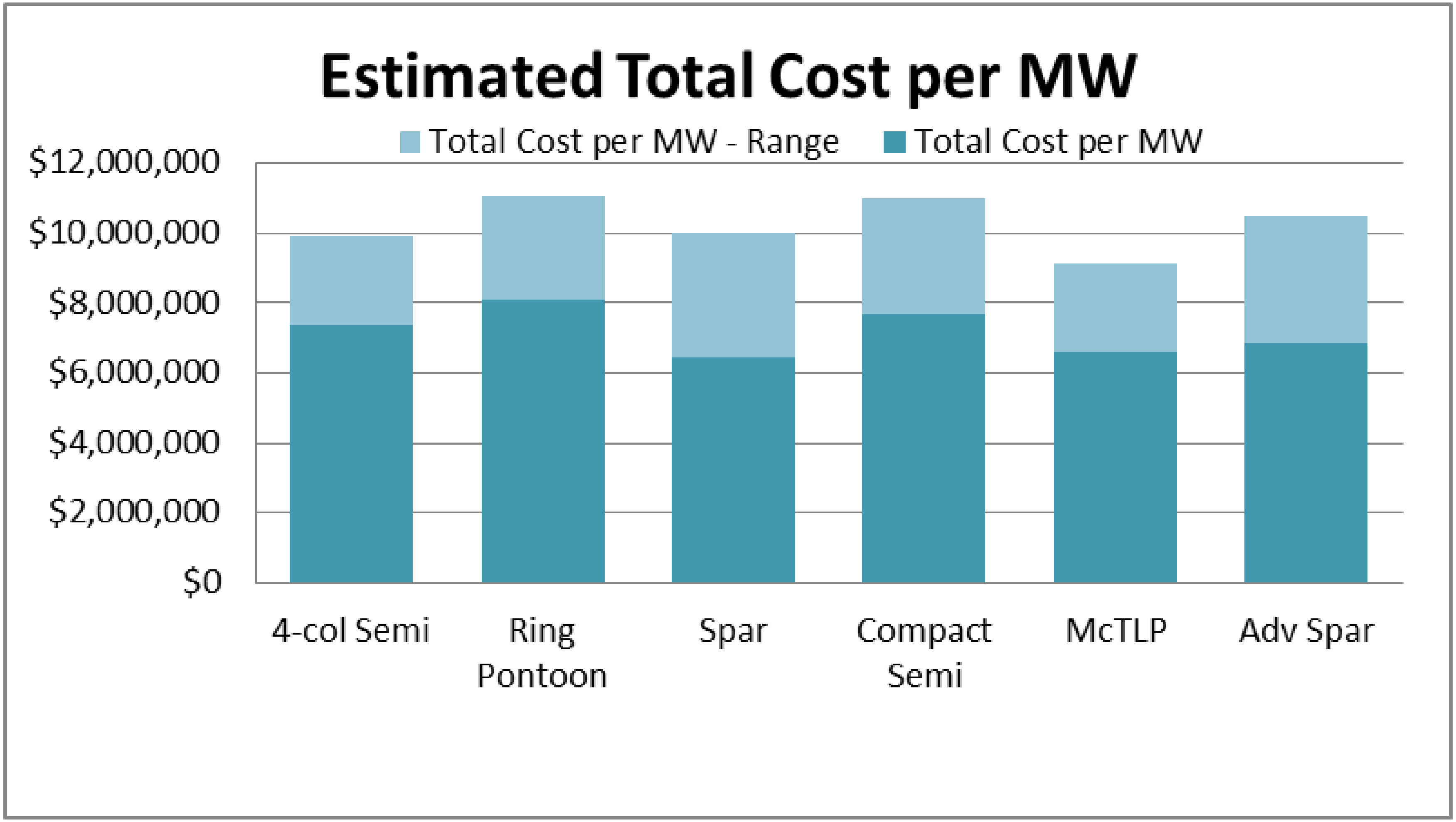








Offshore VAWT Platform Costs/MW



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Phase 1 Cost Estimate

• 4 Column Semi	\$7.4 M/MW-\$ 9.9 M/MW
• Ring Pontoon	\$8.1 M/MW-\$11.0 M/MW
• Spar	\$6.4 M/MW-\$10.0 M/MW
• Compact Semisubmersible	\$7.7 M/MW-\$11.0 M/MW
• Multi-Cell TLP	\$6.6 M/MW-\$ 9.1 M/MW
• Advanced Spar	\$6.8 M/MW-\$10.5 M/MW

Summary

Phase 1 Concept Scorecard

					Floating Platform Technical Challenges Platform Stability Classifications						
Platform Design Challenge Parameters	**Tech**	**Capex**	**Opex**	**Reliability**	**Buoyancy (Ring Pontoon Barge)**	**Ballast (Classic Spar)**	**Buoyancy + Ballast (Semi-Sub)**	**Transformer (Compact Semi)**	**Game-changer (Cellular TLP)**	**Combo (Advanced Spar)**	**Explanation**
Essential Design Features											
Less than 1 G lateral acceleration	X				-						TBD but Ring Pontoon Barge has largest wave zone area
Quasi-Static Rotor Torque Compatibility	X										TBD
Dynamic Rotor Compatibility in torque, pitch, and roll	X				-						TBD but Ring Pontoon Barge has large wave area
Anchor Pile Spacing Less than 800m	X	-	-	-					+		TBD but CTLP anchors are directly below columns
Float Out Complete/Dry Dock for Blade Repair		X	X		+		+	+	+	+	TBD if ASpar can tow vertically, CSpar has separate hull & deck tows
Amenable to Mass Production		X				+			+	+	Based on multiple pieces of same size and shape
Mooring Line Redundancy				X							TBD
Preferred Design Features											
Minimize Hull Fabrication/Assembly		X				+				-	Cspar constructed horizontally, ASpar constructed vertically
Minimize Hull Special Materials/Equipment		X							+		No mechanical fairleads required for CTLP
Minimize Hull Marine Systems & Outfitting		X	X		-	+				+	Semis require most compartmentation, RPB may need double hull
Minimize Above Water Deck and Hull Steel	-	X	-	-		+				+	Spars have but single column above water and compact deck
Minimize Mooring Line Material/Anchor	-	X	-	-					+		CTLP uses wire rope for tendons and requires minimal lengths
Minimize Mooring Line Pre-Install/Hook-up		X							+		CTLP has pre-installed piles, wire rope tendons are pre-rigged on hull
Minimize Hull Installation		X				-					CSpar requires upending operation, fixed ballast and deck installation
Minimize Mooring Line Replacement			X						+		Wire rope tendon can be replaced from top of column using ROV
Minimize Hull/Mooring Structural IM			X			+					Cspar has fewest compartments to inspect
Minimize Decommissioning			X			-				-	CSpar will require reverse upending, Aspar will require re-floating
Beneficial Design Features											
Scalable to Larger Turbines		X									TBD
Water Depth Scalability		X									TBD
Field Proven Hull/Mooring Performance				X	-	+	+	-		-	Cspars and Semis have been used in oil and gas industry
Ease of Generator Removal/Replacement			X			+				+	Spars provides closest work barge access for generator replacement
Minimize Offset/Motions for Power Cable Design		X	X	X	-						TBD but Ring Pontoon Barge may have higher motions due to wave area
Minimize Drive Train Housing Wave Reinforcement		X	X	X		+					CSpar float over deck is at highest elevation
Impact of Stability Class on Turbine Design					**Buoyancy (Barge)**	**Ballast (Spar)**	**Buoyancy + Ballast (Semi-Sub)**	**Transformer**	**Game-changer**	**Combo**	
Turbine Weight					+	-					
Tower Top Motion					-	-					
Controls Complexity					-	-					
Maximum Heel Angle					-	-					

Key: + = relative advantage
- = relative disadvantage
o = neutral advantage

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Comparison of Phase 1 Concepts

		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
		Four-column Semi	Classic Spar	Ring Pontoon	Compact Semi	Advanced Spar	MC-TLP
Vessel Width at Keel	*m*	37	17	44	37	32	32
Vessel Draft	*m*	10	70	6	11	50	10
Displaced Volume	m^3	5,858	16,213	5,038	4,726	15,200	6,174
Displacement	*kN*	58,895	162,996	50,649	47,511	152,808	62,069
KB	*m*	4	35	2	5	20	4
BM	*m*	8	0.265	9	8	0.283	9
KM	*m*	11	35	12	13	20	13
KG	*m*	7.60	31.14	7.50	9.36	17.66	8.91
GM	*m*	3.58	4.00	4.14	4.00	2.48	4.33
Lightship Weight	*kN*	32,706	48,047	33,099	29,705	46,528	38,069
Vertical Mooring Tension	*kN*	270	270	270	270	270	24,000
Water Ballast	*kN*	25,919	2,000	17,280	17,536	3,521	0
Entrained Water	*kN*	--	112,679	--	--	102,489	--
Total Supported Weight	*kN*	58,895	162,996	50,649	47,511	152,808	62,069
Estimated Fabrication Cost	*million USD*	27 - 36	21 - 34	31 - 42	28 - 42	23 - 37	26 - 36
Estimated Mooring Cost	*million USD*	4.1 - 5.2	4.1 - 5.2	4.1 - 5.2	4.1 - 5.2	4.1 - 5.2	2.1 - 2.8
Estimated Installation Cost	*million USD*	5.8 - 8.1	6.8 - 10.0	5.8 - 8.1	5.8 - 8.1	7.0 - 9.9	4.3 - 6.2
Estimated Total Cost	*million USD*	37 - 50	32 - 50	41 - 55	39 - 55	34 - 53	33 - 46

Summary

Comparison of Phase 1 Concepts

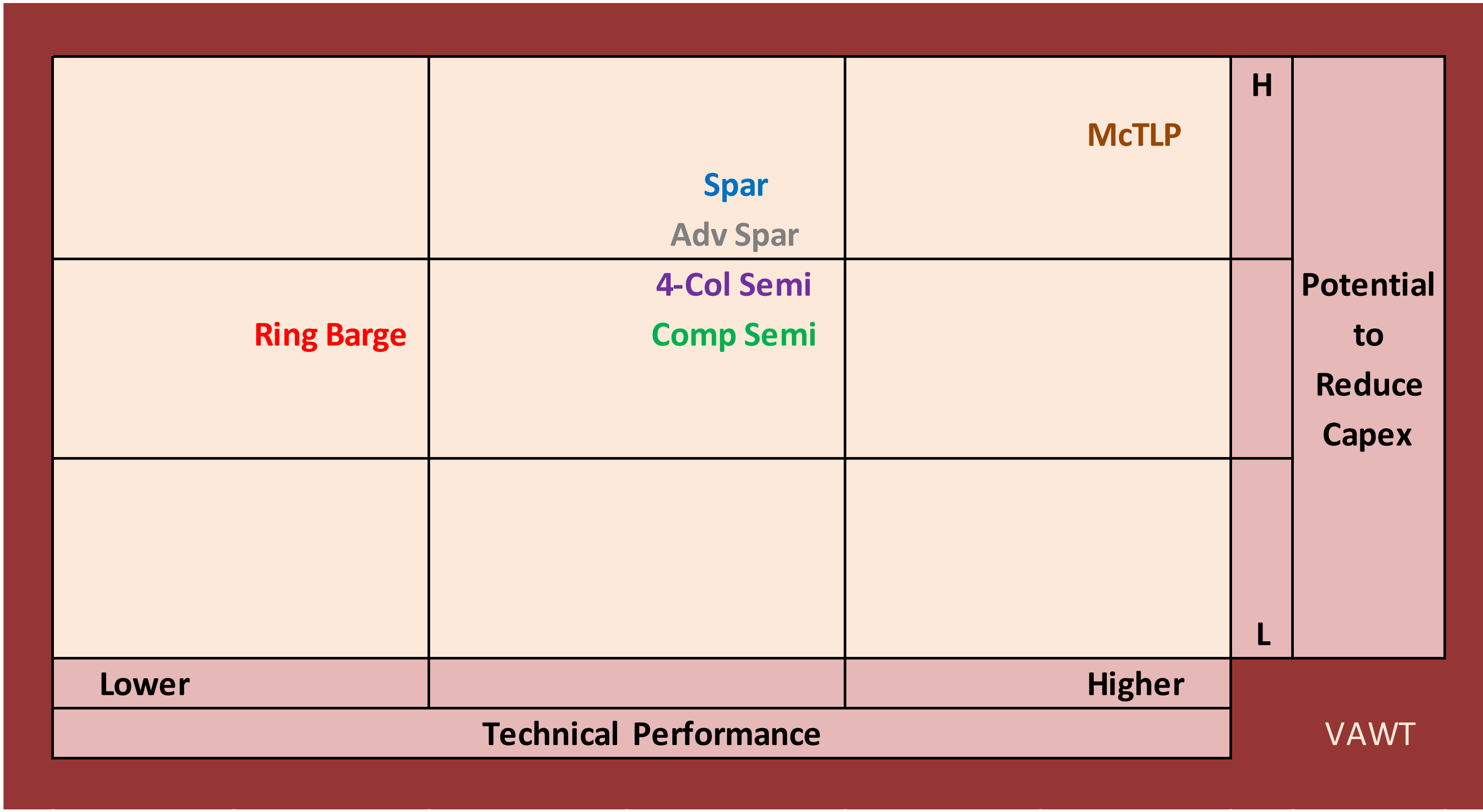
		Concept 1 Four-column Semi	Concept 2 Classic Spar	Concept 3 Ring Pontoon	Concept 4 Compact Semi	Concept 5 Advanced Spar	Concept 6 MC-TLP
K_{11}	*N/m*	1.329E+05	1.348E+05	1.329E+05	1.592E+05	1.380E+05	1.623E+05
K_{22}	*N/m*	1.329E+05	1.348E+05	1.329E+05	1.592E+05	1.380E+05	1.623E+05
K_{33}	*N/m*	1.985E+06	2.327E+06	6.599E+06	3.826E+06	2.362E+06	7.135E+07
K_{44}	*(N-m)/deg*	3.993E+06	1.181E+07	3.977E+06	3.485E+06	9.115E+06	2.340E+08
K_{55}	*(N-m)/deg*	3.995E+06	1.181E+07	3.977E+06	3.485E+06	9.115E+06	2.340E+08
K_{66}	*(N-m)/deg*	1.076E+06	8.189E+05	1.076E+06	1.654E+06	1.384E+06	1.118E+06
M_{11}	*kg*	9.809E+06	3.061E+07	8.730E+06	8.558E+06	3.251E+07	7.388E+06
M_{22}	*kg*	9.781E+06	3.061E+07	8.730E+06	8.558E+06	3.251E+07	7.388E+06
M_{33}	*kg*	1.891E+07	1.791E+07	3.365E+07	7.959E+06	2.611E+07	1.341E+07
I_{44}	*kg-m* ^{2}	3.635E+09	5.210E+10	5.678E+09	1.794E+09	5.275E+10	2.337E+09
I_{55}	*kg-m* ^{2}	3.651E+09	5.214E+10	5.711E+09	1.827E+09	5.278E+10	2.369E+09
I_{66}	*kg-m* ^{2}	2.436E+09	6.536E+08	9.287E+08	1.305E+09	6.151E+08	1.374E+09
T_{11}	*sec*	54	95	51	46	96	42
T_{22}	*sec*	54	95	51	46	96	42
T_{33}	*sec*	19	17	14	9	21	3
T_{44}	*sec*	25	55	31	19	63	3
T_{55}	*sec*	25	55	31	19	63	3
T_{66}	*sec*	40	23	24	23	17	29

Technical Comparison Parameters

- Less than 1 G lateral acceleration
- Quasi-Static Rotor Torque Compatibility
- Dynamic Rotor Compatibility in torque, pitch, and roll
- Anchor Pile Spacing Less than 800m

Summary

Technical Performance vs CAPEX Reduction



Reliability Comparison Parameters

- Mooring Line Redundancy
- Field Proven Hull/Mooring Performance
- Minimize Offset/Motions for Power Cable Design
- Minimize Drive Train Housing Wave Reinforcement

Concept Reliability vs CAPEX Reduction

	McTLP Adv Spar	Spar	H	Potential to Reduce Capex
Ring Barge	Comp Semi	4-Col Semi		
			L	
Lower		Higher		
Concept Reliability				VAWT

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OPEX Parameters

- Float Out Complete/Dry Dock for Blade Repair
- Minimize Hull Marine Systems & Outfitting
- Minimize Mooring Line Replacement
- Minimize Hull/Mooring Structural IM
- Minimize Decommissioning
- Ease of Generator Removal/Replacement
- Minimize Offset/Motions for Power Cable Design
- Minimize Drive Train Housing Wave Reinforcement

Minimize OPEX vs CAPEX Reduction

	McTLP	Spar Adv Spar	H	Potential to Reduce Capex
	4-Col Semi Ring Barge Comp Semi			
			L	
Lower		Higher		
Minimize Opex				VAWT

Limitations of This Report

This report is prepared for the sole benefit of Sandia National Laboratories, and the scope is limited to matters expressly covered within the text. In preparing this report, Stress Engineering Services, Inc. (SES) has relied on information provided by Sandia National Laboratories and, if requested by Sandia National Laboratories, third parties. SES may not have made an independent investigation as to the accuracy or completeness of such information unless specifically requested by Sandia National Laboratories or otherwise required. Any inaccuracy, omission, or change in the information or circumstances on which this report is based may affect the recommendations, findings, and conclusions expressed in this report. SES has prepared this report in accordance with the standard of care appropriate for competent professionals in the relevant discipline and the generally applicable industry standards. However, SES is not able to direct or control operation or maintenance of Sandia National Laboratories's equipment or processes.

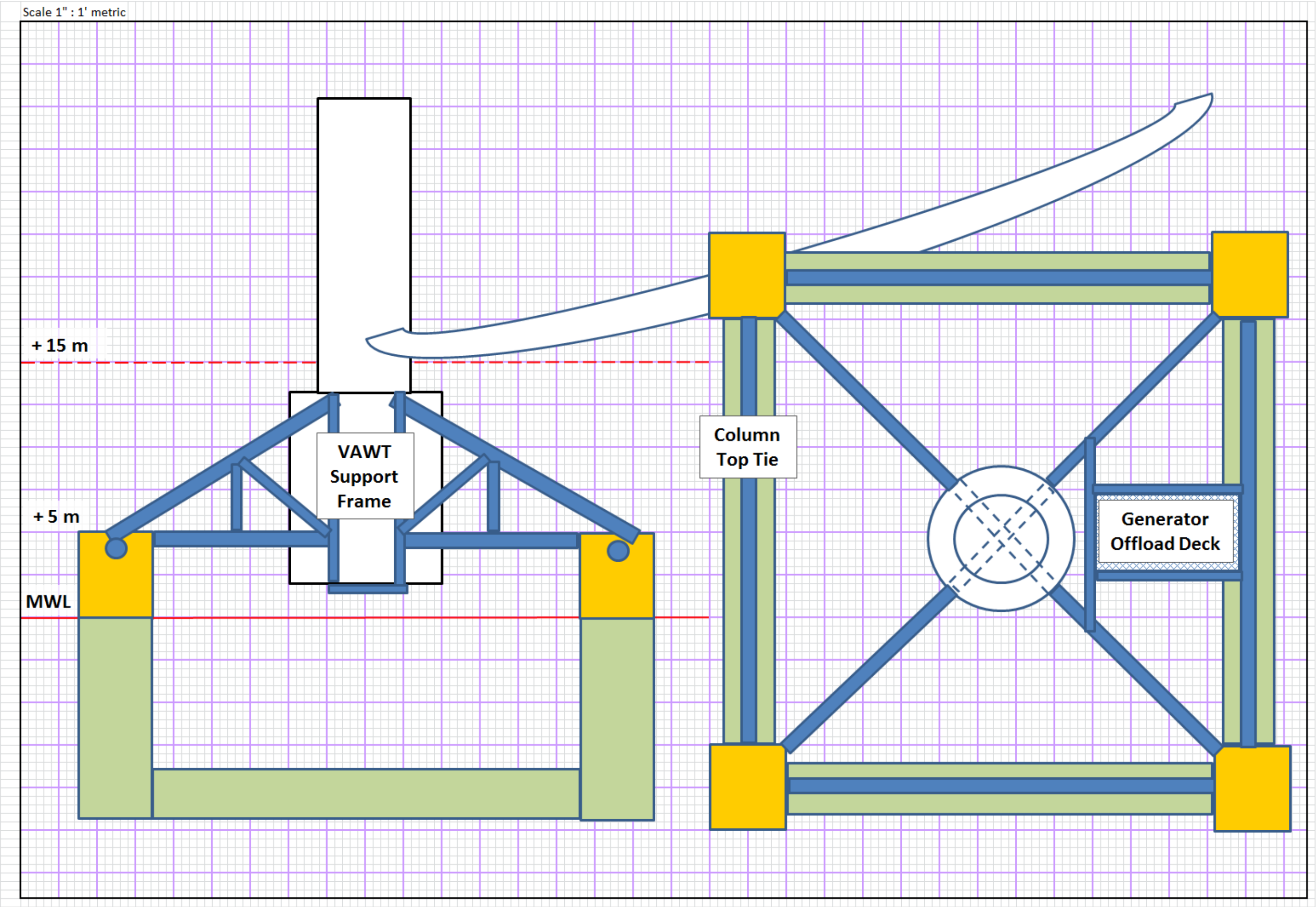
Rev	Date	Description	Originator	Checker	Reviewer
A	10-Mar-2016	Issued for Internal Review	Chad Searcy Steve Perryman	N/A	N/A
B	21-Mar-2016	Issued for Client Review	Chad Searcy Steve Perryman	John Chappell	John Chappell

Appendix A

Logistical Considerations

Logistical Considerations

Deck Steel for Four-column Semi



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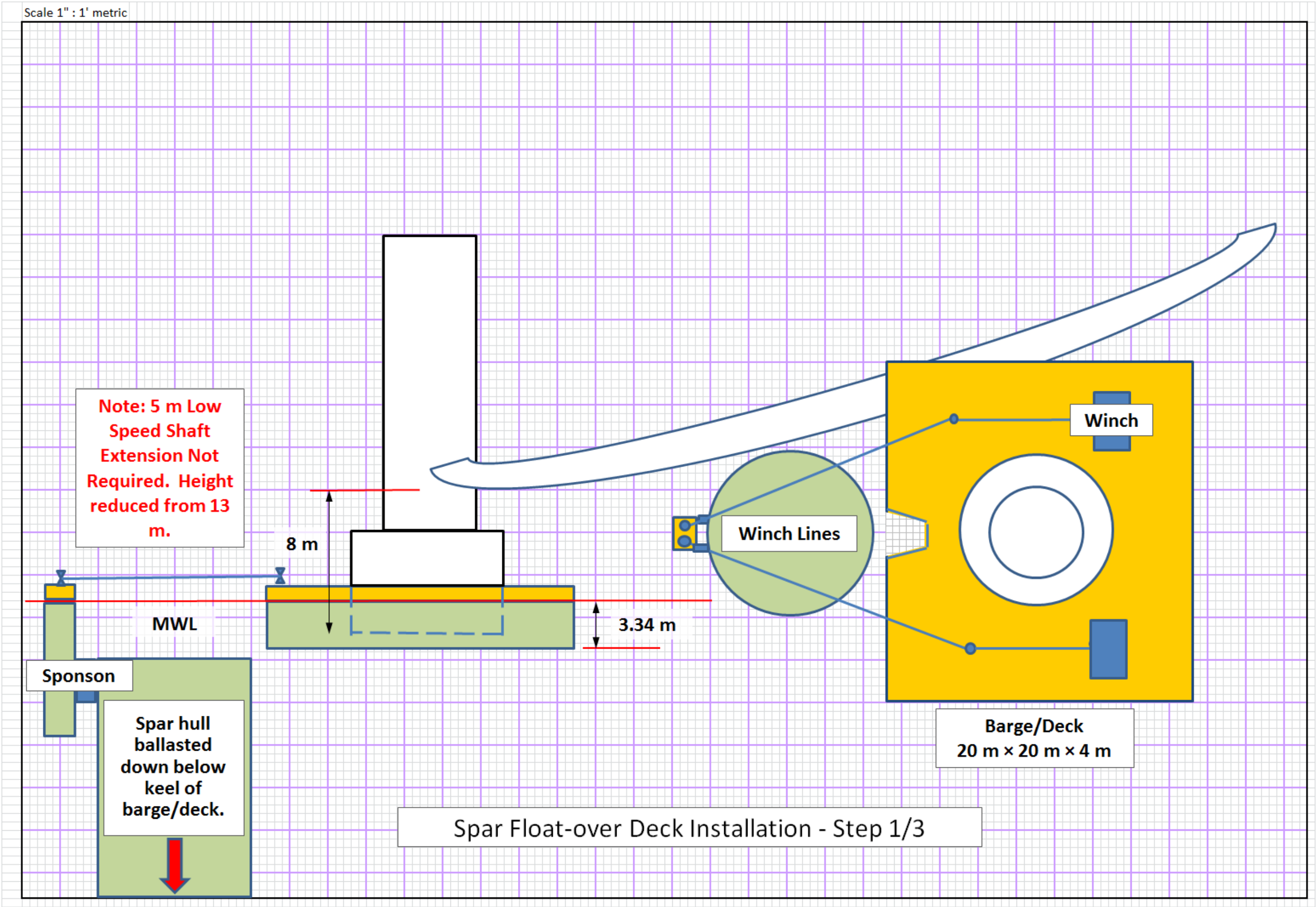
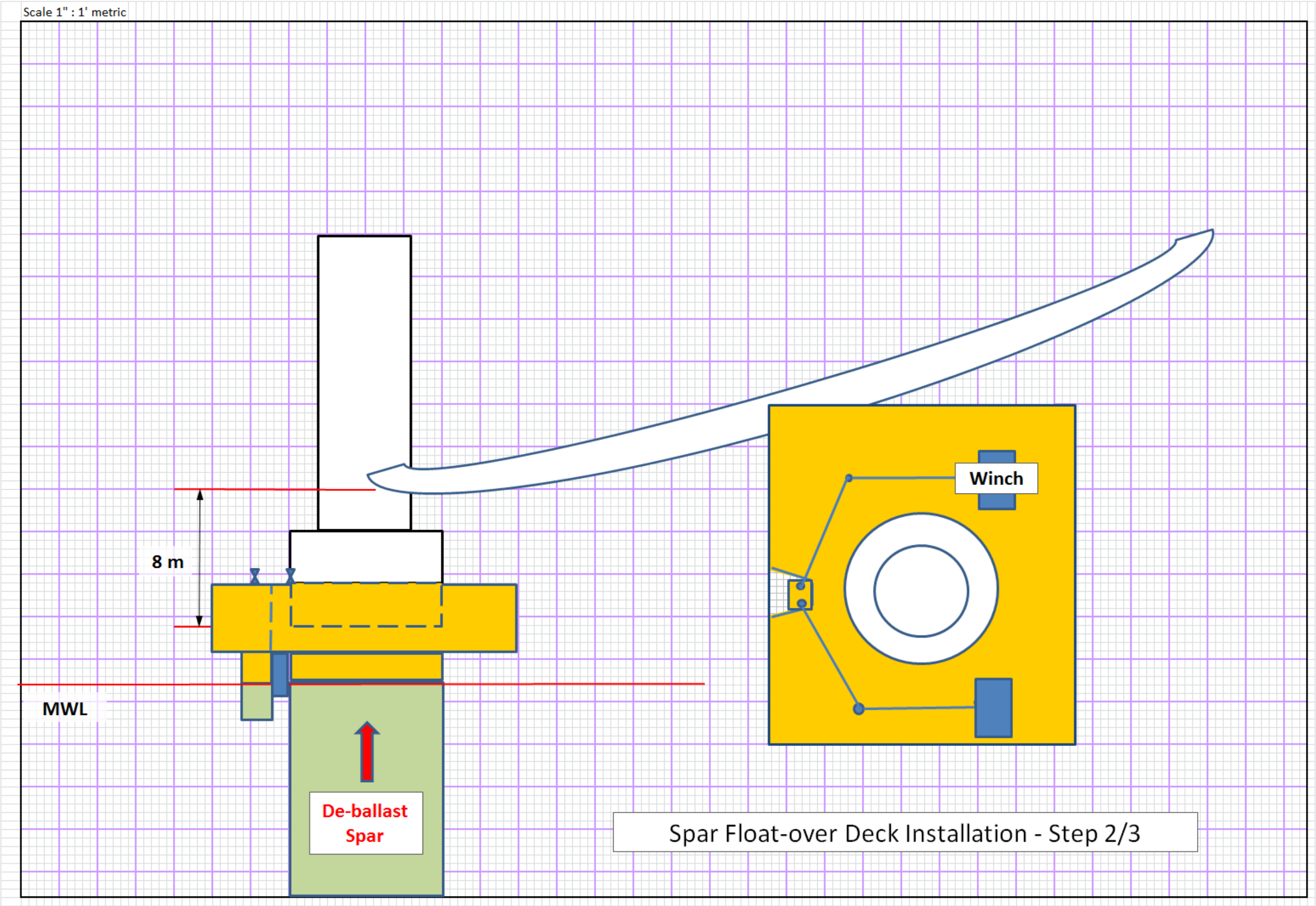
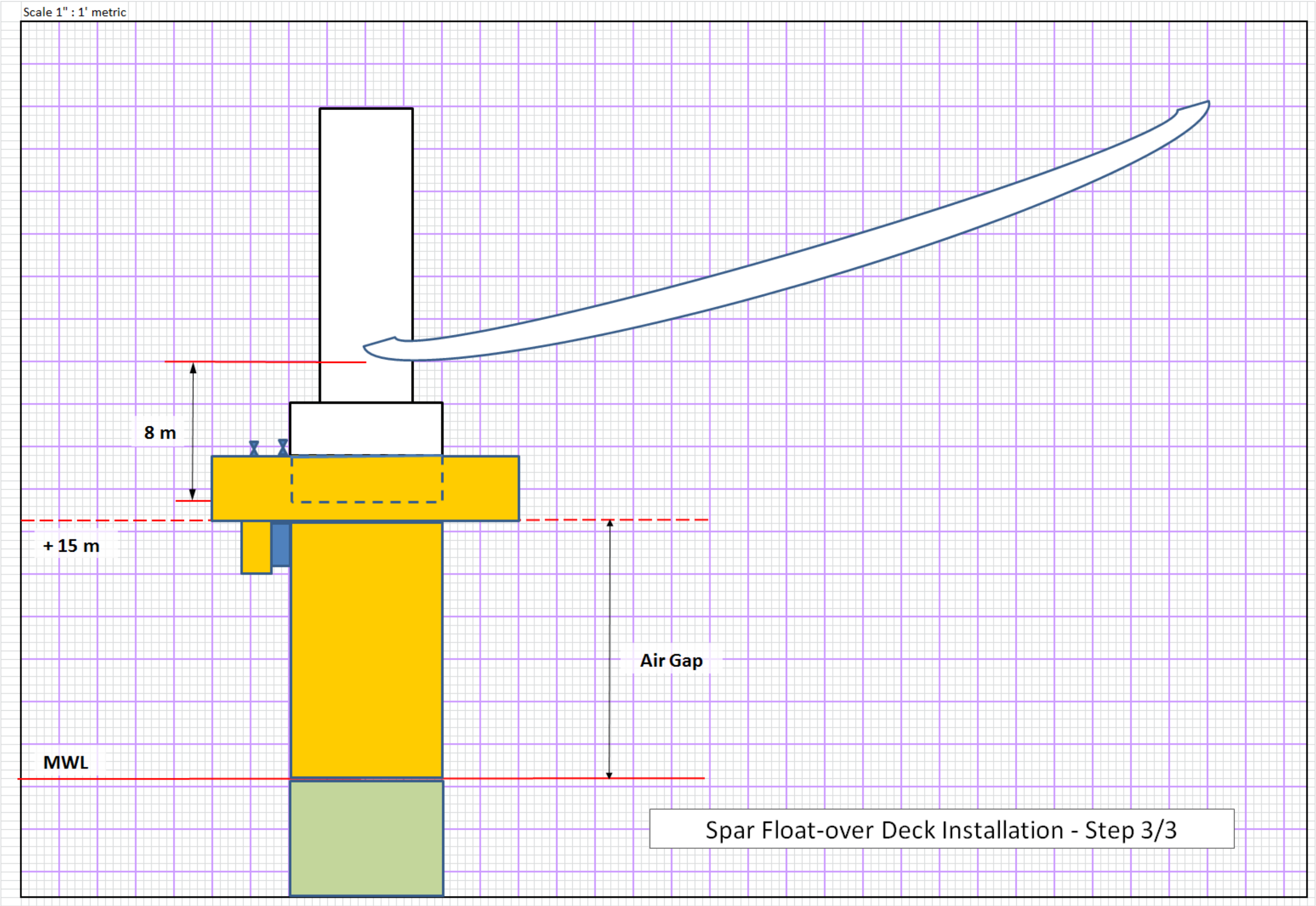
Classic Spar Float-over Deck (1/3)



Classic Spar Float-over Deck (2/3)

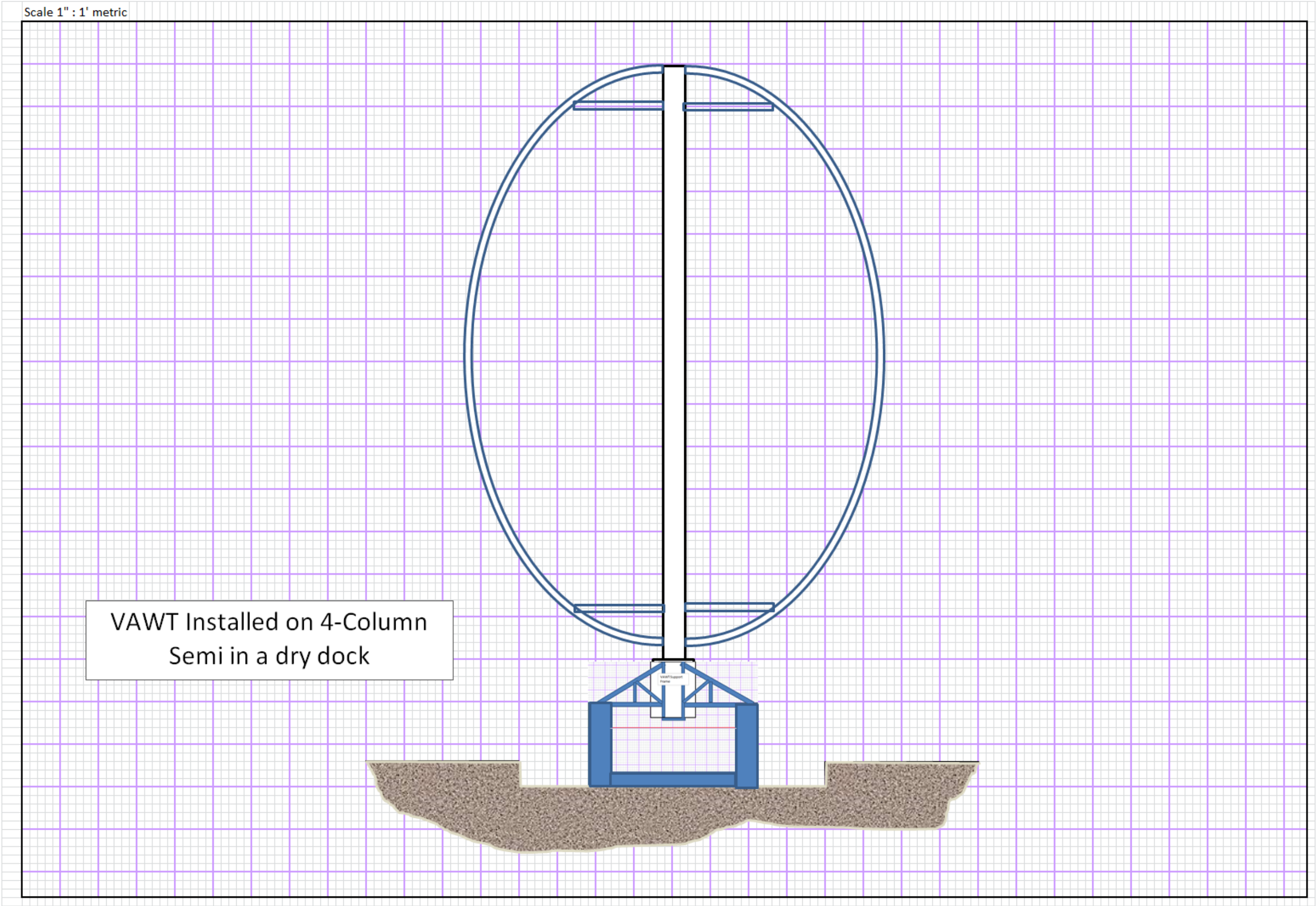


Classic Spar Float-over Deck (3/3)



Logistical Considerations

VAWT Installation in Dry Dock



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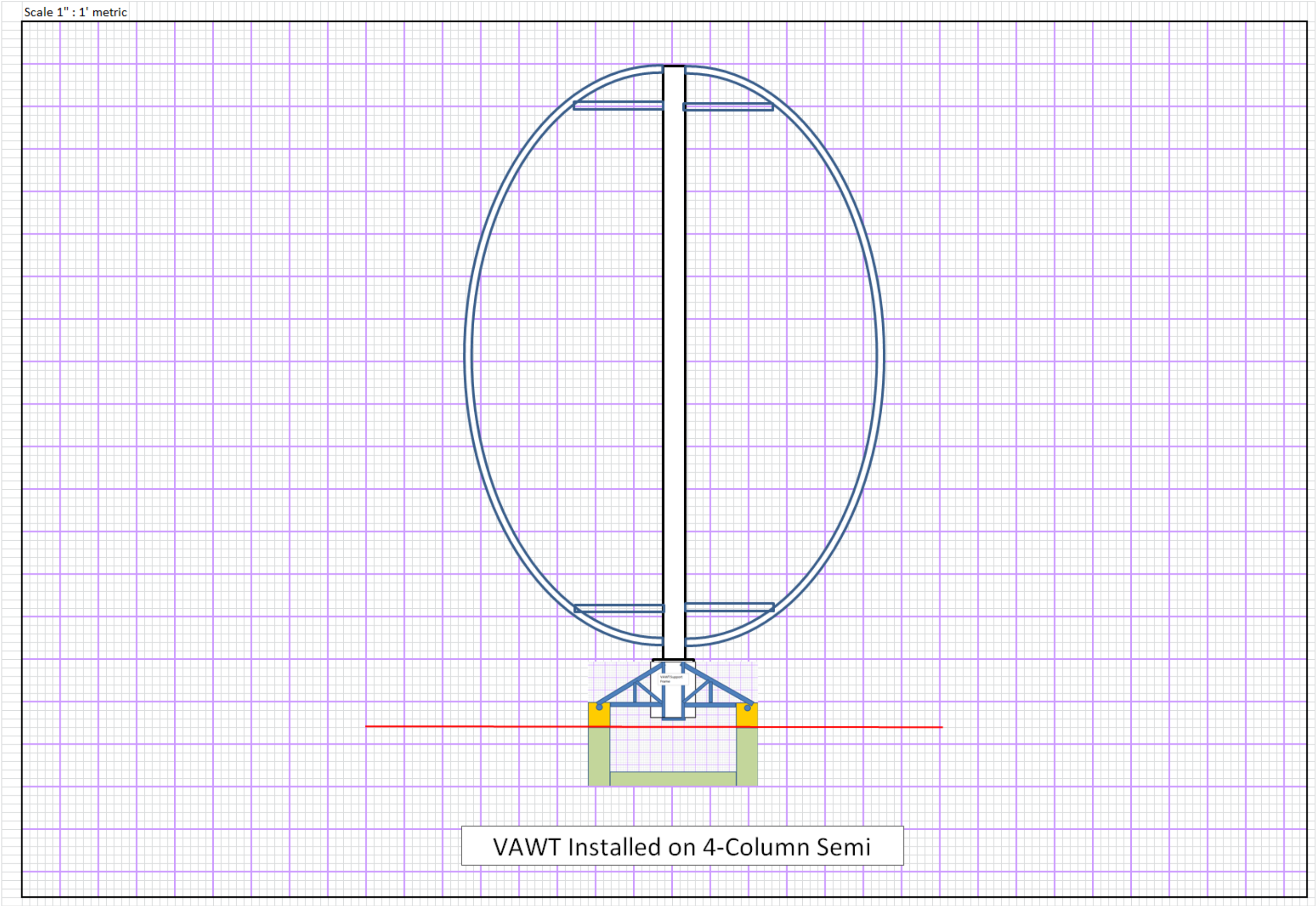
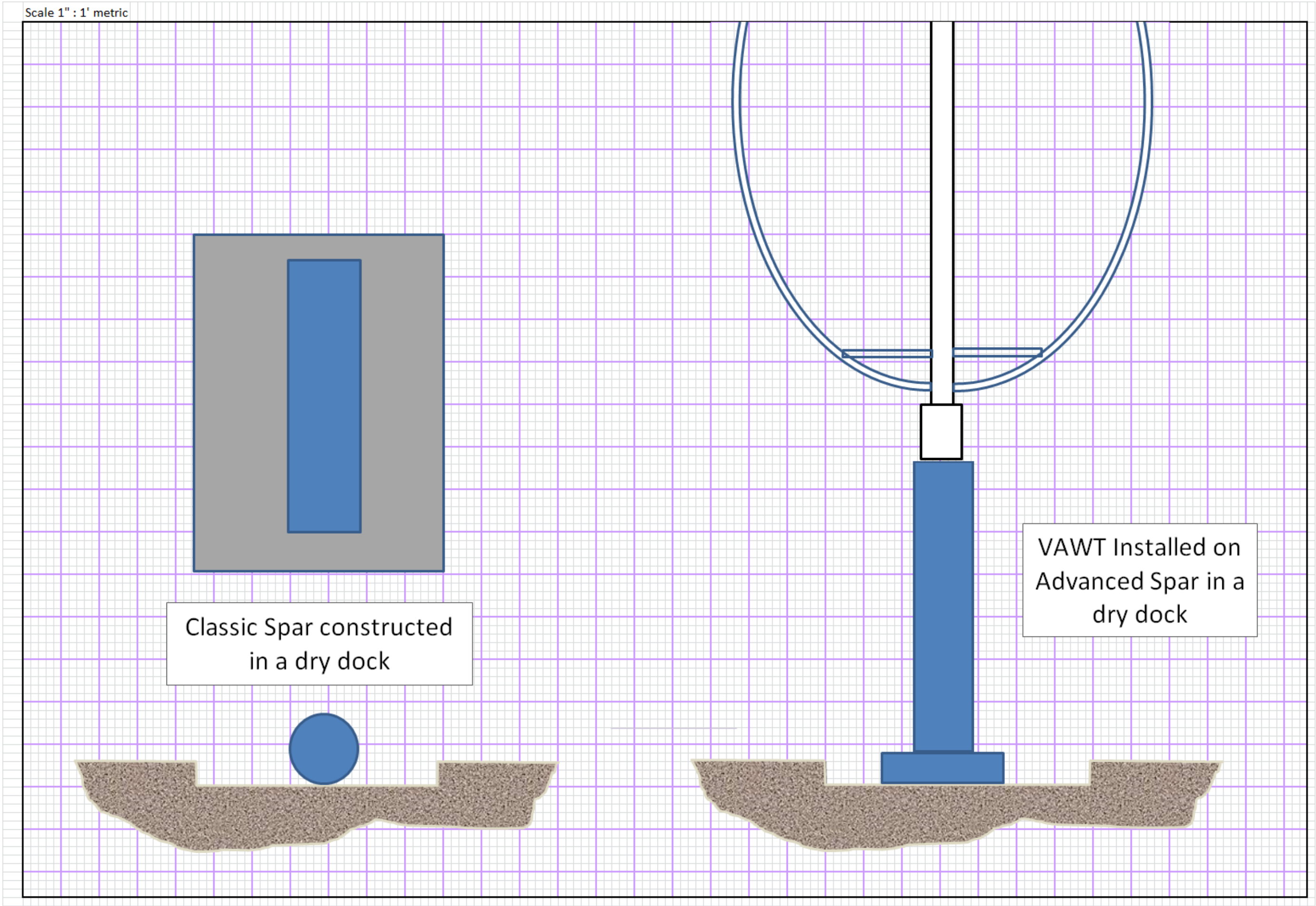
Logistical Considerations

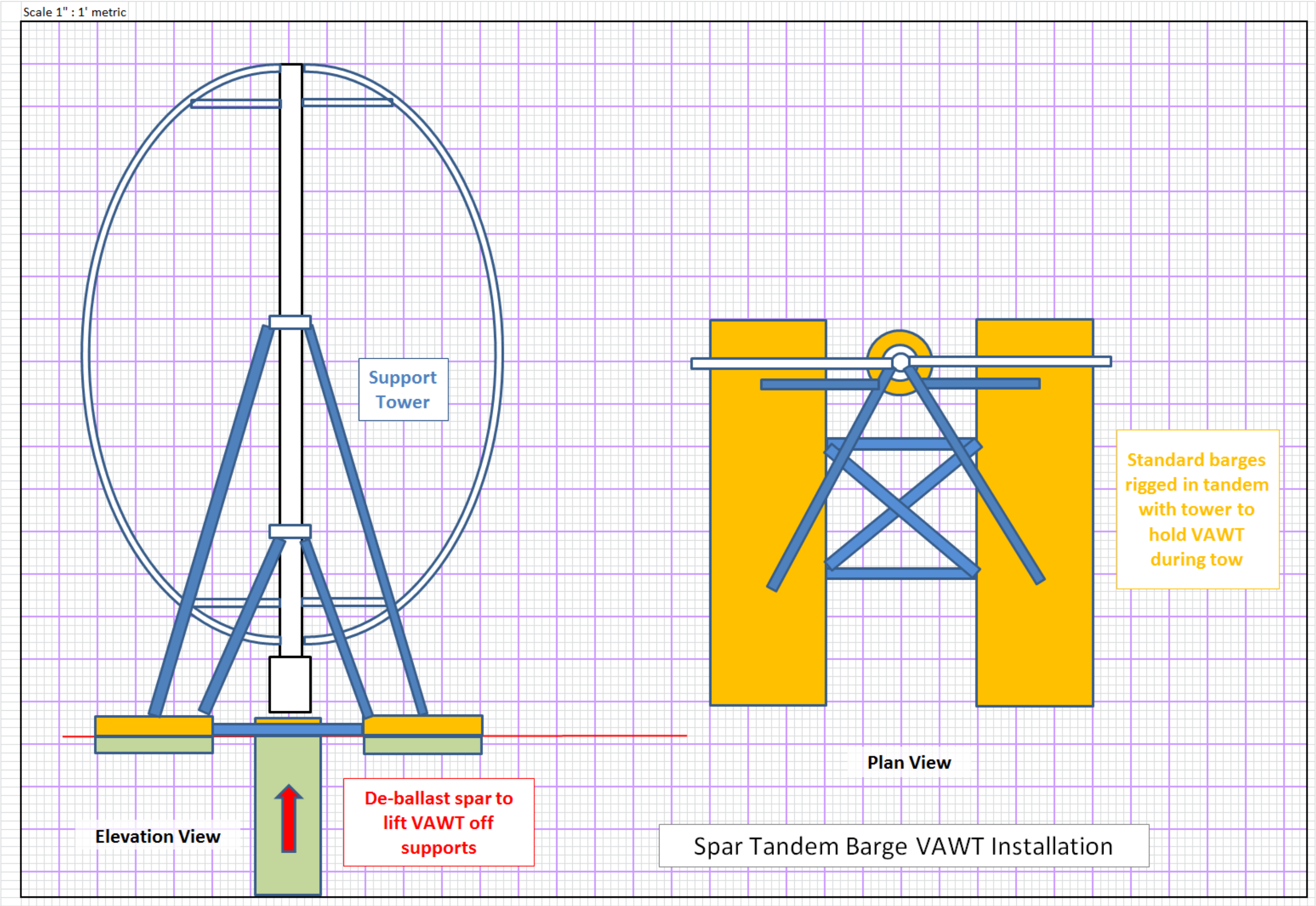
Installed Four-column Semi



Classic Spar vs Advanced Spar in Dry Dock



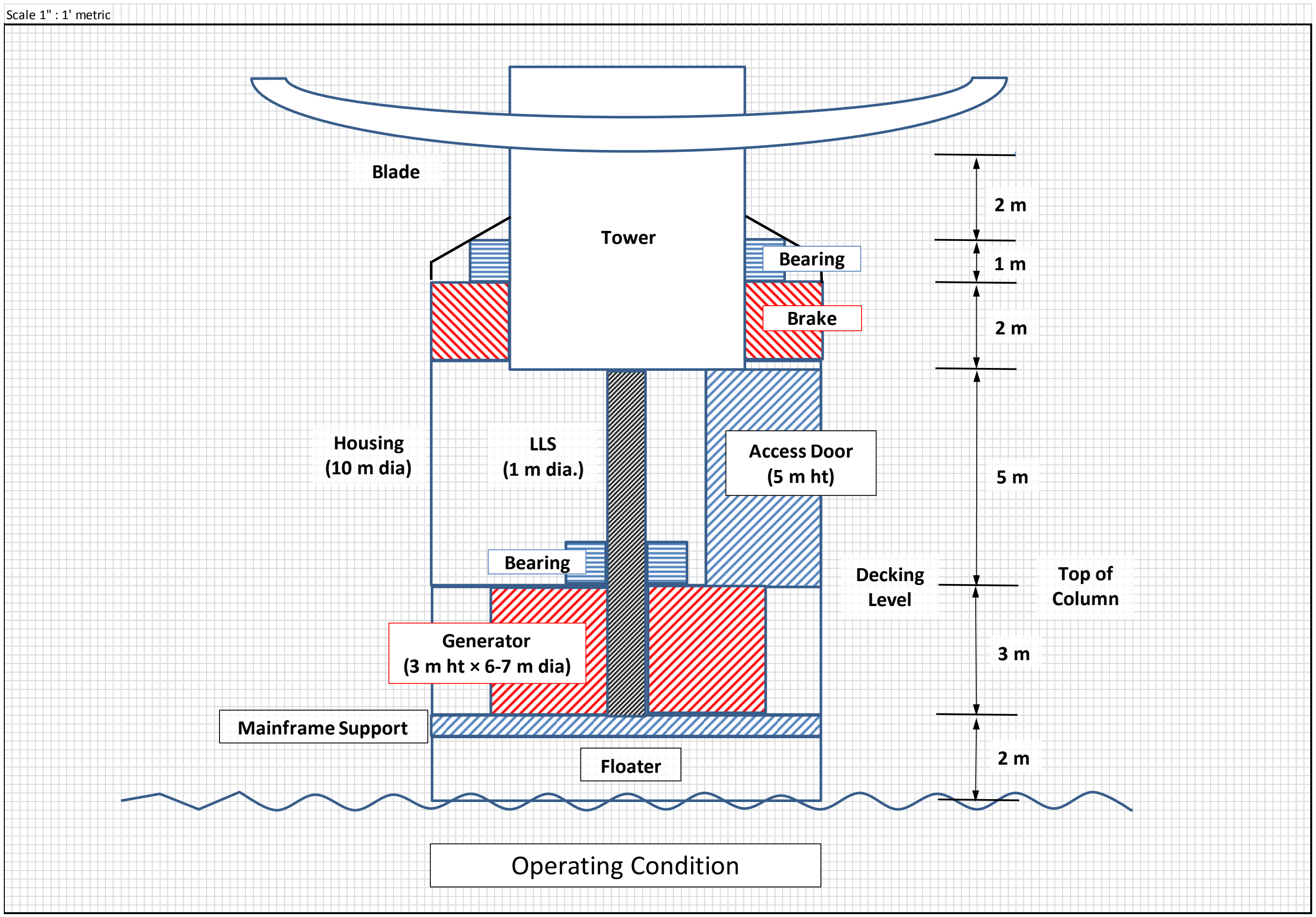
Spar Tandem Barge for VAWT Installation



Logistical Considerations

Generator Removal

Step A



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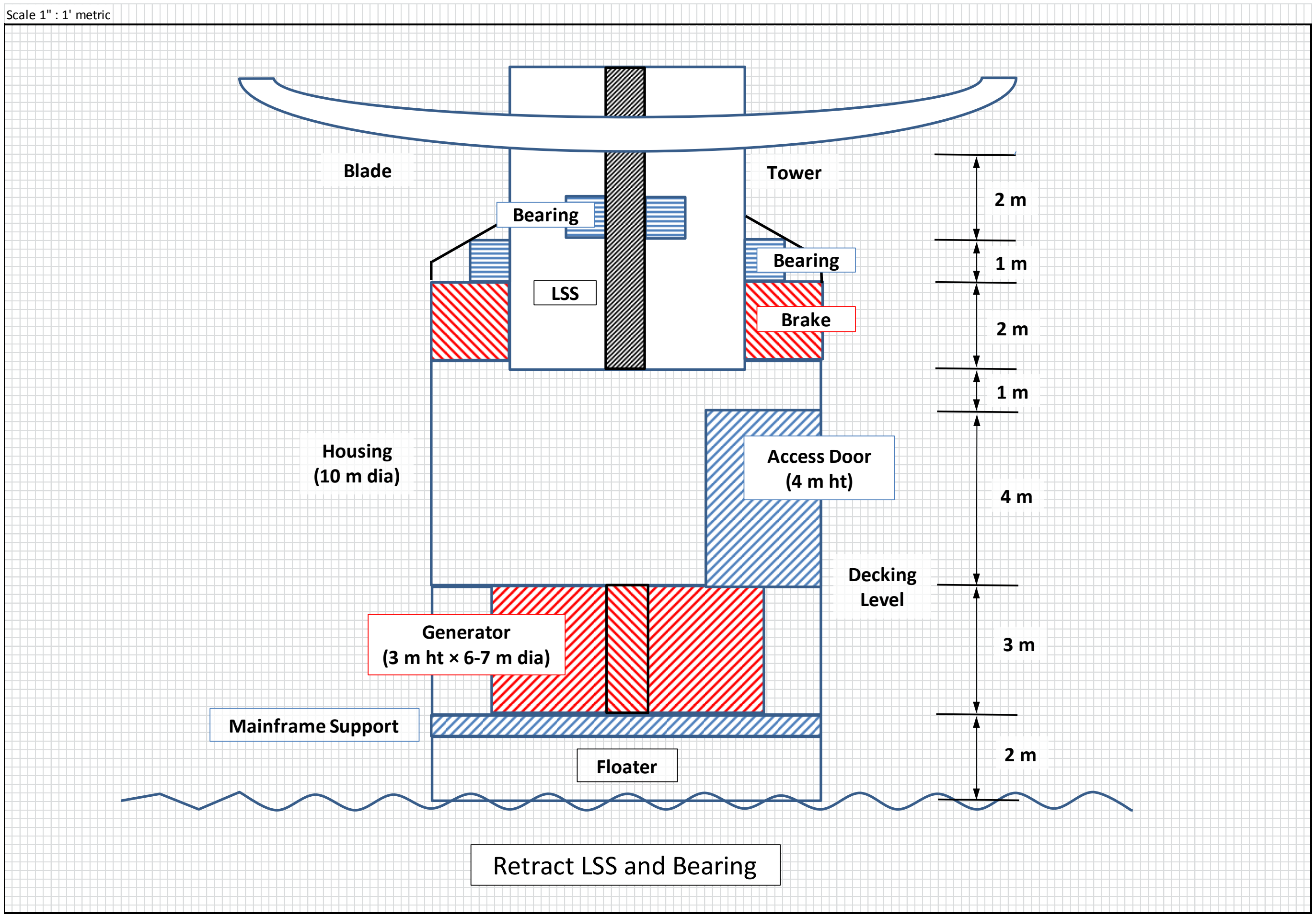
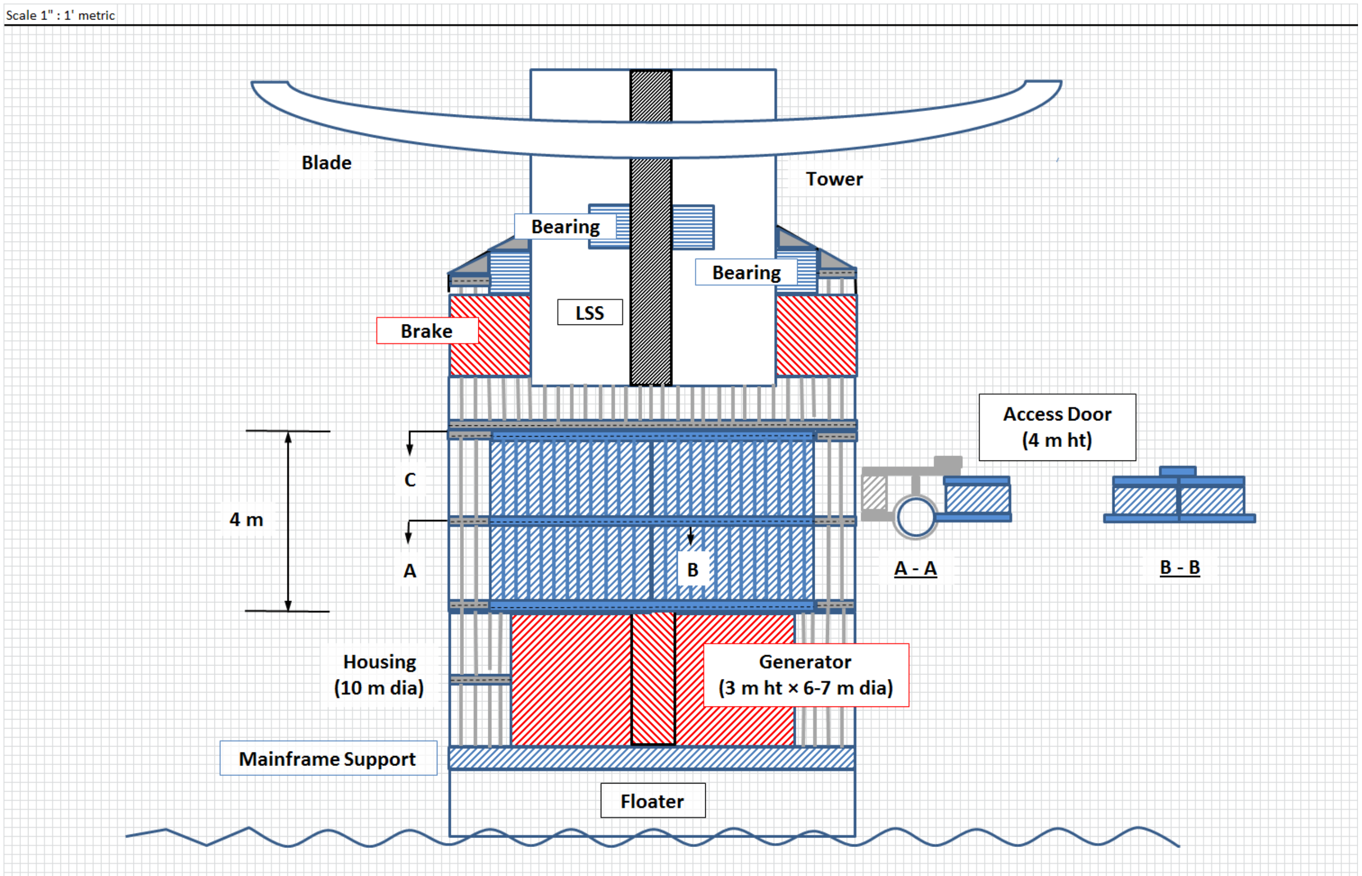
Generator Removal

Step B



Generator Removal

Step C

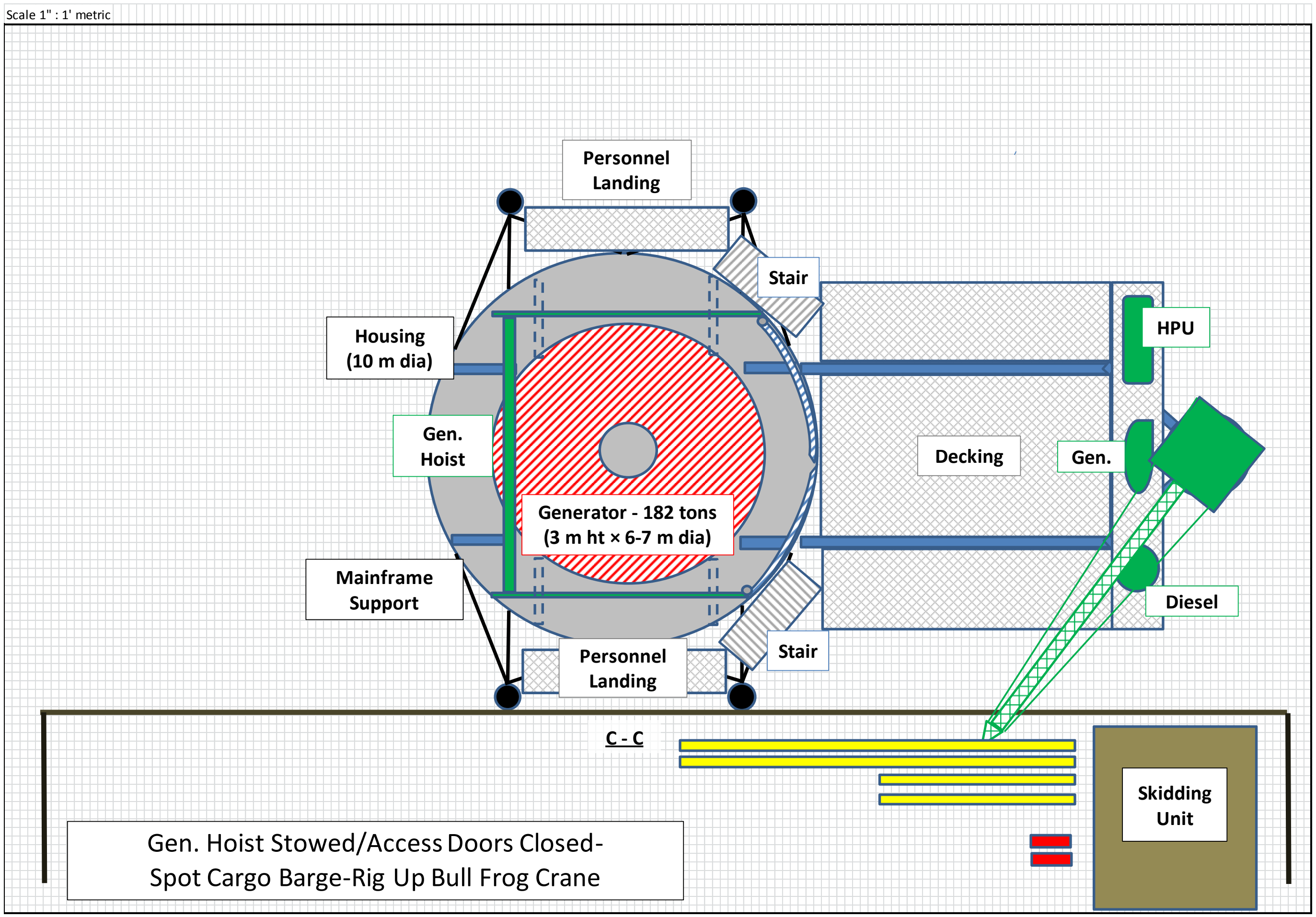


Typical Stiffening, Access Doors & Hinges

Logistical Considerations

Generator Removal

Step D



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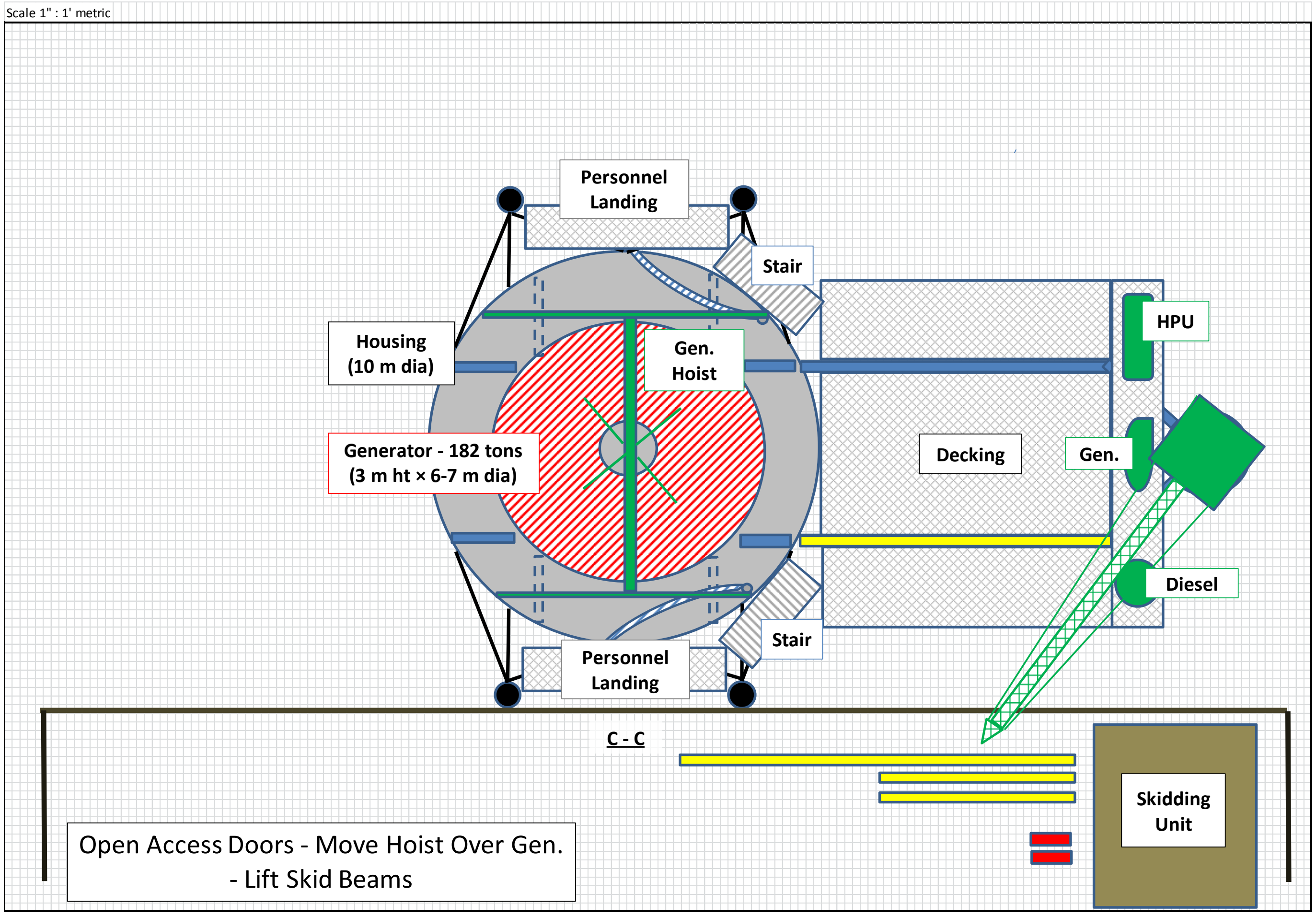
Logistical Considerations

Generator Removal

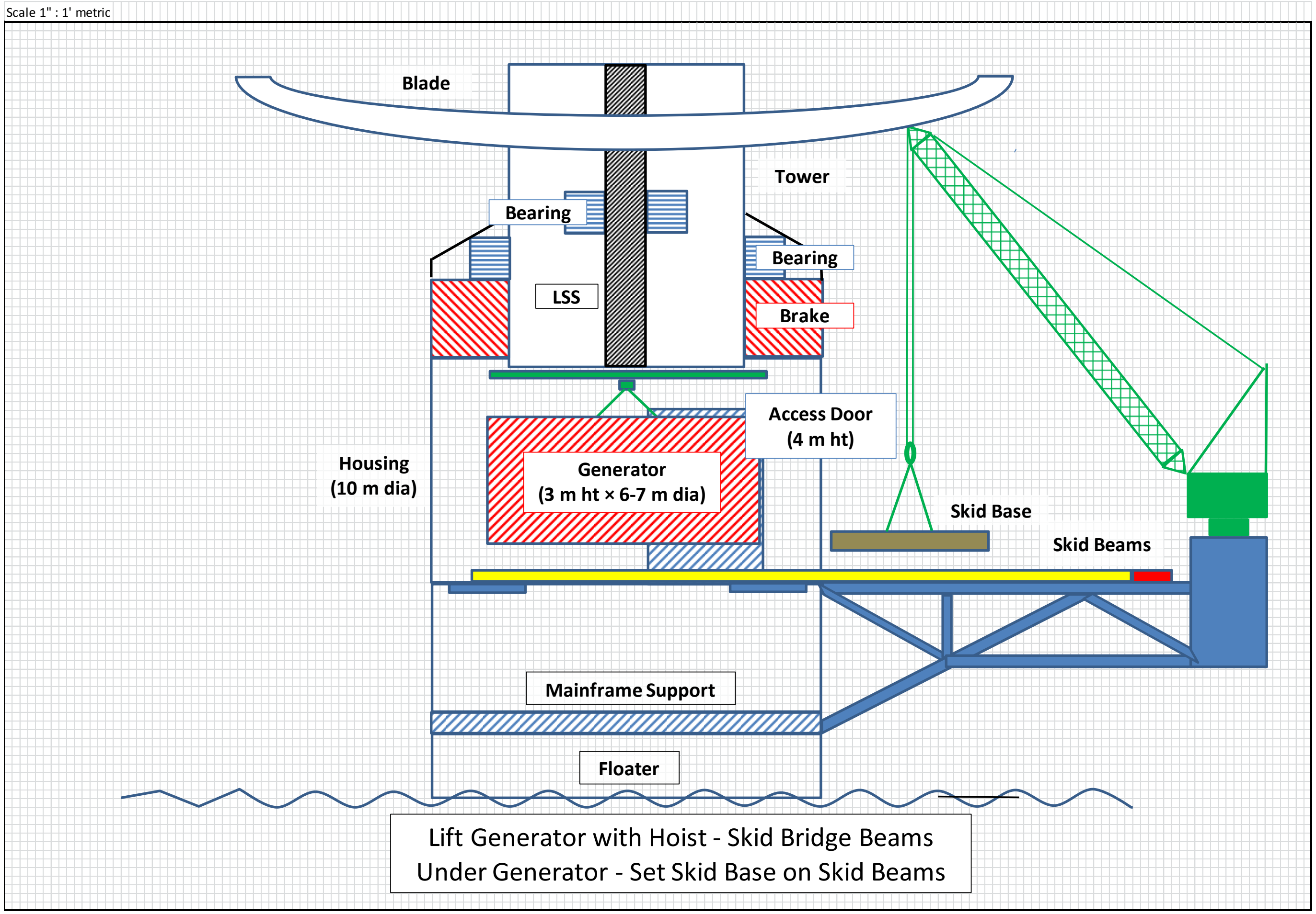
Step E



Logistical Considerations

Generator Removal

Step F



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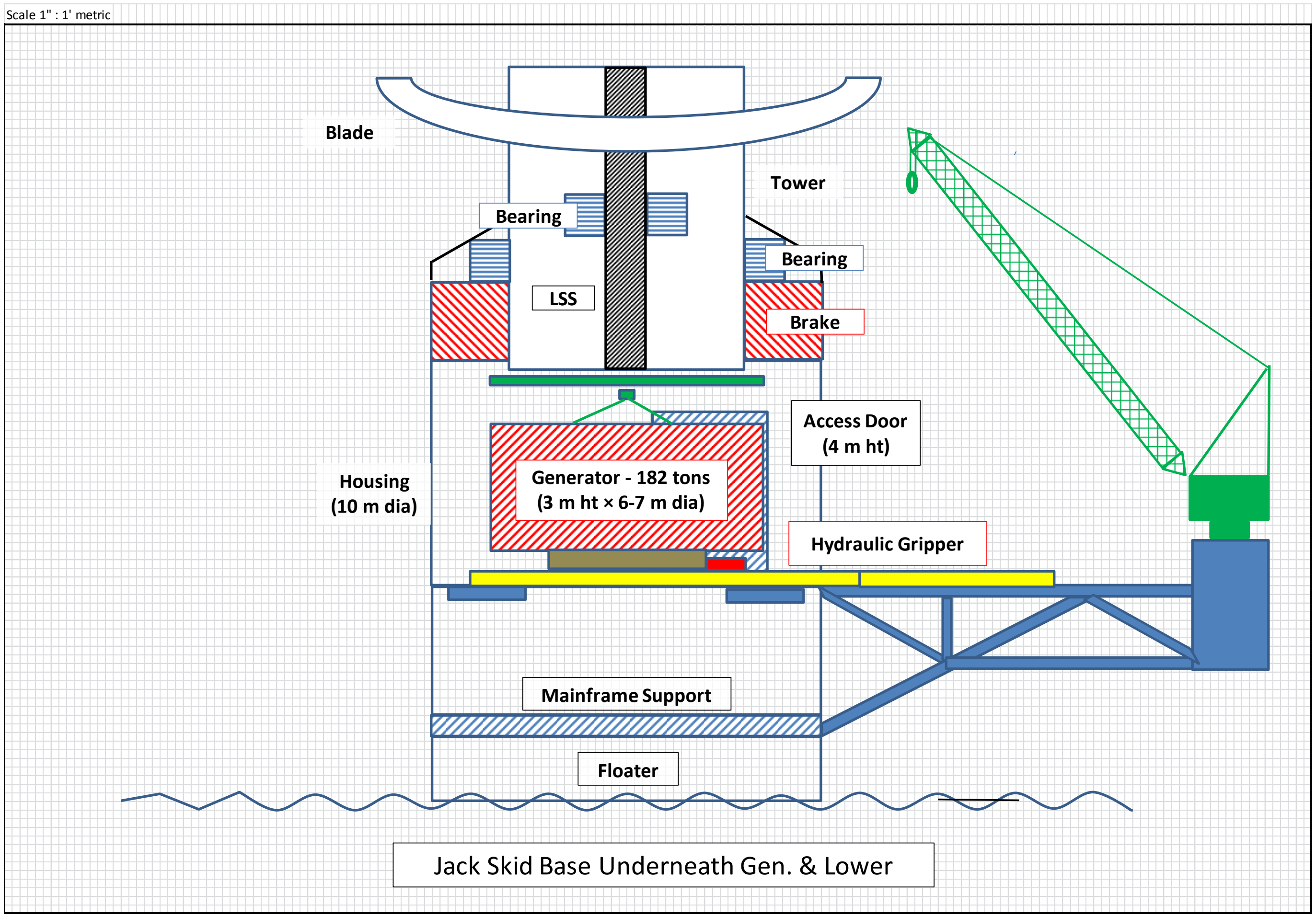
Logistical Considerations

Generator Removal

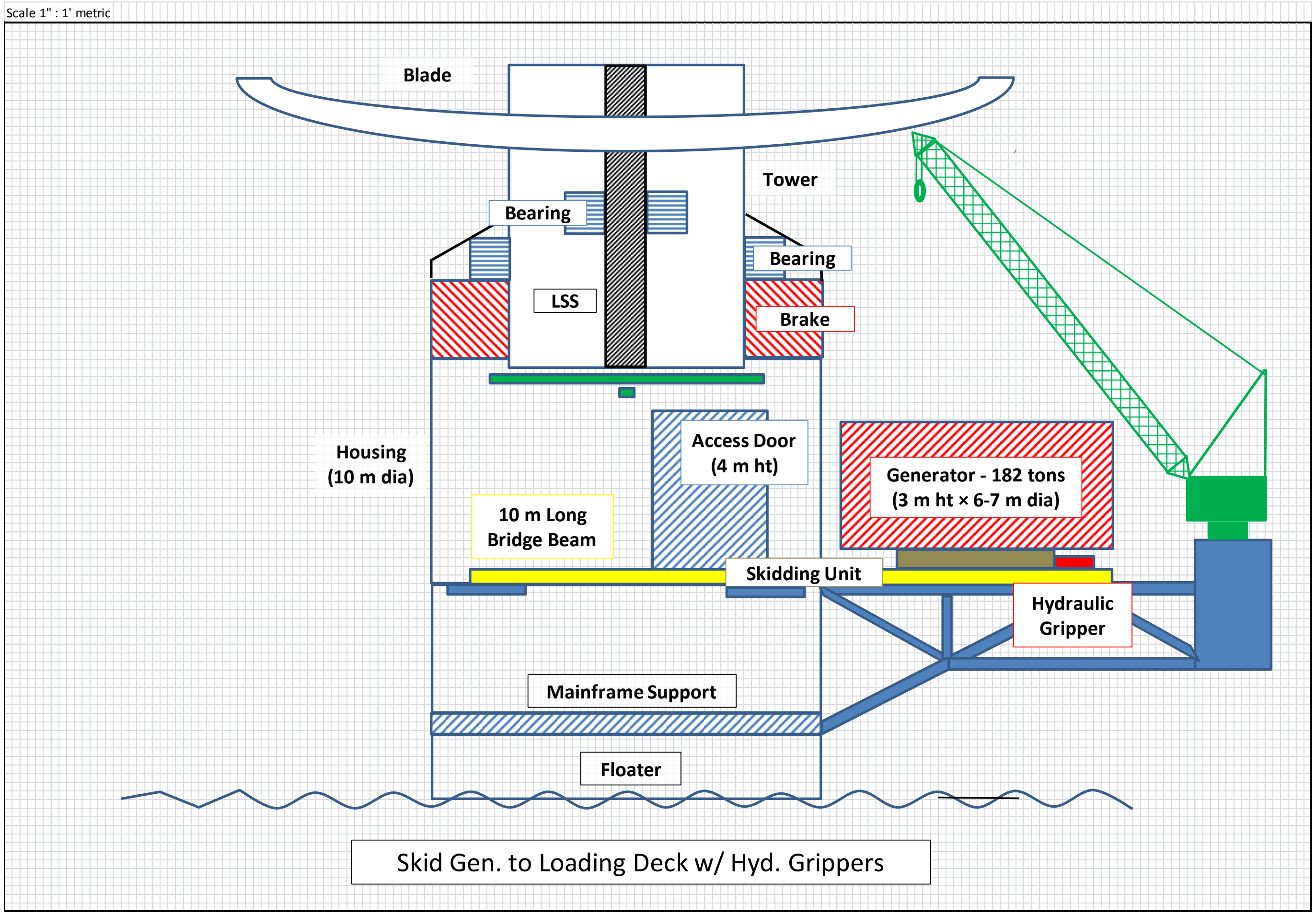
Step G



Logistical Considerations

Generator Removal

Step H



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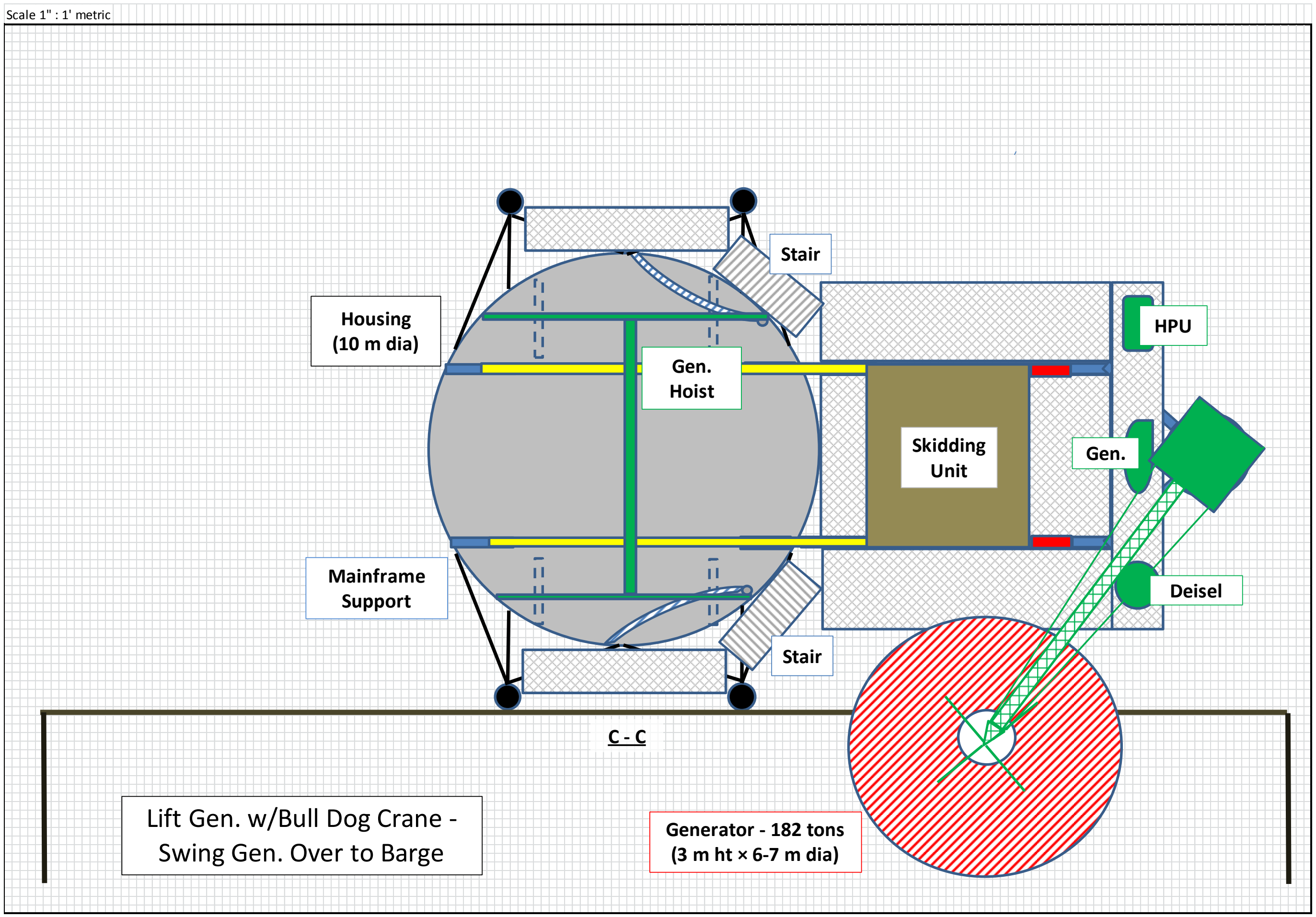
Logistical Considerations

Generator Removal

Step I



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Appendix B

Phase 2 Detailed Platform Deign and Cost Estimation

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Platform and Mooring System Design for a Vertical Axis Wind Turbine (VAWT)

Final Report

Prepared for:

Sandia National Laboratories

Albuquerque, NM

2 June 2017

SES Document No.: 1102668-EN-RP-01 (Rev 0)

Rev	Date	Description	Originator	Reviewer	Approver (Sandia National Laboratories)
A	21-Apr-2017	Issued for Internal Review	Chad Searcy Steve Perryman	N/A	N/A
B	15-May-2017	Issued for Client Review	Chad Searcy Steve Perryman	John Chappell Dilip Maniar	N/A
0	2-Jun-2017	Issued Client Use	Chad Searcy Steve Perryman	John Chappell Dilip Maniar	Todd Griffith

Platform and Mooring System Design for a Vertical Axis Wind Turbine (VAWT)

Final Report

SES Document No.: 1102668-EN-RP-01 (Rev 0)

2 June 2017

Prepared for:

Sandia National Laboratories

Albuquerque, NM

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Executive Summary

Sandia National Laboratories and its partners in government, academia, and industry have been investigating the economic potential and technical feasibility of floating offshore vertical axis wind turbines (VAWTs). In an offshore setting, VAWTs offer multiple cost-competitive advantages over other rotor configurations, namely horizontal axis wind turbines (HAWTs). These advantages are due primarily to having a unique arrangement which places the gearbox, generator, and other related components at the base of the turbine close to the ocean surface. This placement provides service operators with easier access to high maintenance systems, which reduces the risk of maintenance operations, and thus helps reduce the cost of energy. More importantly, this placement lowers the topside center of gravity which enables designers to meet platform stability and motions requirements using smaller and less costly platforms.

In an effort to gain further confidence in the economic viability of floating offshore VAWTs, SNL requested Stress Engineering Services, Inc. (SES) to provide a design and associated cost analysis for a floating platform and mooring system specifically tailored for a VAWT installed in water depths around 150 m. To meet this objective SES proposed a scope of work structured into two (2) phases: an initial screening study of potential floating concepts (Phase 1) followed by a down-select process leading to a single candidate to be chosen for further design work and cost estimation (Phase2). This study was based on SES' independent perception of each floating system concept considered, and no one outside of SES has endorsed or verified SES' work.

In Phase 1, SES surveyed dozens of floating system concepts in search of promising candidates that could be tailored to support a 5MW VAWT. During this survey, these concepts were qualitatively evaluated according to a range of criteria associated with a variety of essential, preferred, and beneficial design features. Among the dozens of concepts considered, six were chosen for Phase 1 design:

- **Concept #1 - Four-column semi-submersible**: a traditional concept that has extensive field-proven performance and offers the ability to tow-out with the turbine fully installed.
- **Concept #2 - Classic spar**: a traditional deep-draft concept that has extensive field-proven performance and is amenable to mass production.
- **Concept #3 - Ring pontoon**: a novel water-plane stabilized concept, inspired by a design developed by IDEOL, was chosen for its simplicity of design and its potential ability to tow-out with the turbine fully installed.
- **Concept #4 - Compact semi-submersible:** a novel variant of the traditional semi-submersible, which is inspired by a concept developed by Mitsui Engineering and Shipbuilding, may offer comparable performance with reduced material costs.
- **Concept #5 - Advanced spar**: a novel variant of the classic spar, inspired by a design developed by Japan Marine United, potentially offers comparable performance with the ability to tow-out with the turbine fully installed.
- **Concept #6 - Multi-cellular tension leg platform (McTLP)**: a mooring-stabilized multi-cellular hull concept, inspired by a design by Petroneering, which is amenable to mass production.

Collectively, these six concepts capture the breadth of stability mechanisms available to floating systems: deep-draft ballasting, vessel waterplane area, and tensioned mooring. Each of these concepts utilizes one or more of these three mechanisms in its design.

For Phase 1 design, SES conducted a preliminary sizing study of the six selected floating system concepts in their operational configurations. These concepts were sized to support the topsides (e.g., turbine, generator, gearbox) and preliminary design constraints (e.g. maximum allowable angular displacements, array spacing, etc.) as specified by SNL. Hydrostatic calculations were performed. Lightship weight was minimized. Fundamental stability was checked. System natural periods were calculated and used to identify potential resonance issues associated with the peak period of the 50-year design seastate and the 2P and 4P periods of the VAWT rotating loads.

Of these six candidates, SES and SNL decided that the McTLP offers the best combination of performance and cost to select it for Phase 2 design. Among the McTLP's key features are:

- **Ability to Tow-out with Topsides Installed:** Both the McTLP and four-column semi-submersible offer this feature. The classic spar concept would require a two-phase installation process.
- **Small Pitch-Roll Motions which Increase Wind Energy Capture:** The McTLP offers this feature. The classic spar and four-column semi-submersible exhibit larger pitch-roll motions.
- **Small Mooring Footprint which Simplifies Seafloor Layout and Enables More Compact Field Arrangements:** Of all the concepts considered in Phase 1, only the McTLP offers this feature.
- **Multi-cellular Structure is Amenable to Mass Production**: All Phase 1 hull concepts feature compartmentalization which could facilitate the fabrication and assembly process; however, the McTLP displays the largest potential to reduce capital expenditure costs via mass production.

For the Phase 2 design effort, SES further developed the McTLP platform and mooring concept through a series of hydrodynamic motion response analyses using the SES proprietary software RAMS (Rational Approach to Marine Systems). Global performance of the platform/mooring model in the frequency domain was performed for two environmental load cases: a non-operating extreme event load case with a 50-year return period with the turbine parked and a maximum operating load case with turbine loads provided by SNL. As part of the iterative process for this design phase, SES provided stiffness, mass, and damping characteristics of the McTLP concept to SNL for the purpose of re-evaluating the VAWT loads and vessel motions. For this study, SES performed four design iterations to arrive at a reasonably sized platform and mooring system that meets the performance metrics set by SES and SNL. A rendering of the Patran model used in the hydrodynamic analysis of this McTLP hull is provided in Figure 1. The particulars associated with this final preliminary design are summarized in Table 1.

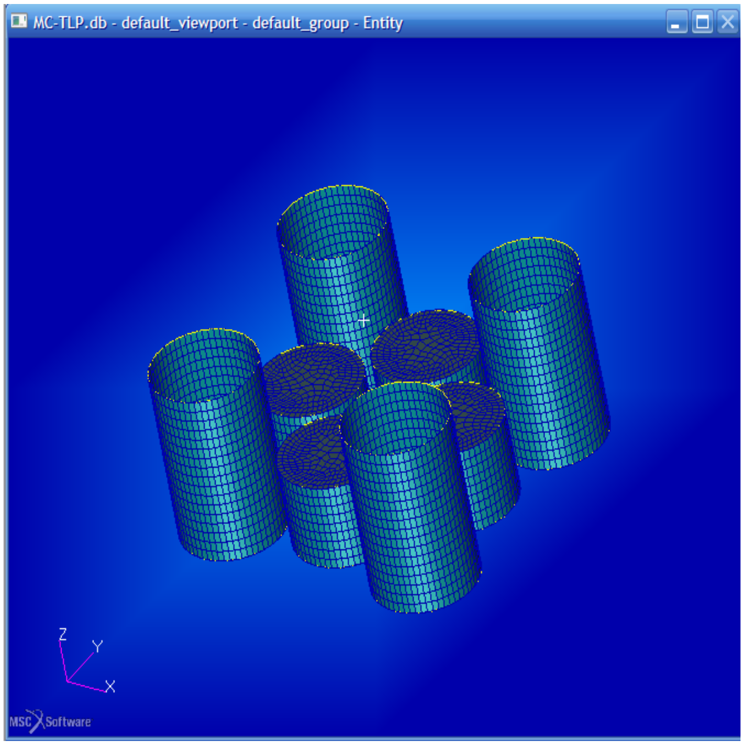

Figure 1: Patran Model of McTLP Hull

Table 1: Particulars for 5MW VAWT McTLP

Parameter		Value			
Displacement		98,627	*kN*	22,172	*kips*
Operational Draft		17.2	*m*	56	*ft*
Vessel Span		33.7	*m*	111	*ft*
Pontoon Cell Diameter		11	*m*	36	*ft*
Pontoon Height		8.6	*m*	28	*ft*
Column Cell Diameter		11	*m*	36	*ft*
Column Height		27	*m*	89	*ft*
Freeboard		20	*m*	66	*ft*
Turbine Height (above mean water line)		150	*m*	492	*ft*
Lightship		34,148	*kN*	7,677	*kips*
Mooring Tension (per tendon)		3,500	*kN*	787	*kips*
Water Ballast		36,478	*kN*	8,201	*kips*
Distance from Keel to Center of Gravity	***KG***	8.4	*m*	28	*ft*
Distance from Center of Gravity to Metacenter	***GM***	4.0	*m*	13	*ft*

A summary of the estimated costs associated with the fabrication and construction of the McTLP hull and mooring system (excluding the turbine), as well as the transportation and installation of the fully-integrated turbine-hull-mooring system is provided in Table 2. These estimated costs were based on historical cost data from one-of-a-kind deepwater floating oil and gas platforms for major oil companies. The data consisted of three components:

- **Fabrication:** The fabrication data included hull and mooring project management, engineering, overhead and profit and certification. This data took the form of costs per unit hull weight. The costs per unit hull weight were applied to the spreadsheet weights to obtain the hull fabrication costs. Since the historical costs reflected a high level of specifications, typical of major oil companies, a reduction factor was applied to these costs to enable a lower bound which could be obtained via use of more industry wide specifications, particularly since the VAWT platforms will be unmanned.
- **Moorings:** The mooring costs were estimated in similar fashion except that the mooring line costs were estimated on the basis of water depth, to reflect the much shallower depth of the VAWT platforms. Factors were applied to reflect the potential for bridge industry connections to be used versus some customization which may be needed during final design. The factors also allow for some uncertainty in geotechnical information at this time.
- **Installation:** The installation costs were based on typical day rates and reasonable estimates of vessel types and number of days required to potentially execute the field operations. Cost factors were applied to reflect the volatility in installation vessel costs due primarily to vessel availability at any given time. It should be noted that no derrick barge costs were included due to the assumption that none will be needed for the VAWT platforms.

For Phase 2, a factor was applied to the fabrication costs to reflect a volume discount anticipated from such a large steel order, as well as the efficiency which should be gained by producing 100 units. Additionally, the engineering and certification costs were divided by 100, since they do not need to be repeated for each identical VAWT platform. Likewise, the anchor handling vessel mobilization cost was divided by 100, assuming the vessels would work continuously. No weather downtime was specifically included, as it should be included in the day rates.

A summary of the estimated costs associated with the fabrication and construction of the McTLP hull and mooring system (excluding the turbine, drivetrain, and ancillary equipment), as well as the transportation and installation of the fully-integrated turbine-hull-mooring system is provided in Table 2. The long-form versions of these cost estimates, which were submitted to SNL, are located in Appendix I.

Based on the level of design definition achieved at the end of Phase 2, these cost estimates can be considered Class 3 estimates in terms of the system published by AACE International. The expected accuracy range of these estimates is ~+/-20%.

Table 2: McTLP 5MW VAWT Cost Estimate

Item	Lower Bound Cost		Upper Bound Cost	
Project Costs	2.0	*MM USD*	2.7	*MM USD*
Turbine Support Structure	1.0	*MM USD*	1.3	*MM USD*
Interior Columns	3.6	*MM USD*	5.0	*MM USD*
Outer Columns	11.5	*MM USD*	15.9	*MM USD*
Hull Subtotal	**18.1**	***MM USD***	**24.9**	***MM USD***
Tendon Assemblies	0.9	*MM USD*	1.2	*MM USD*
Templates/Piles	1.3	*MM USD*	1.7	*MM USD*
Tendon System Subtotal	**2.2**	***MM USD***	**2.9**	***MM USD***
Installation Subtotal	**4.2**	***MM USD***	**6.3**	***MM USD***
GRAND TOTAL	**24.5**	***MM USD***	**34.0**	***MM USD***

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1. Introduction

Offshore wind energy has increasingly become an important field of interest. Compared to onshore wind energy, offshore wind energy offers the prospect of increased power production due to stronger, more-sustained winds and reduced power transmission costs due to proximity to coastal population centers where power is required. However, as wind turbines continue to extend into deeper waters, the fabrication and installation costs of the floating support structures can significantly reduce the projected economic benefits. Therefore, to increase the competitiveness of offshore wind energy in the global energy market, it is necessary to identify optimal floating offshore wind turbine designs in order to deliver the lowest cost of energy.

Sandia National Laboratories and its partners in government, academia, and industry have been investigating the economic potential and technical feasibility of floating offshore vertical axis wind turbines (VAWTs). In a deep-water offshore setting (i.e. depths greater than 60 m), VAWTs offer multiple cost-competitive advantages over other rotor configurations, namely horizontal axis wind turbines (HAWTs). These advantages are due primarily to having a unique arrangement which places the drivetrain and other related components at the base of the turbine close to the ocean surface. This placement provides service operators with easier access to high maintenance systems, which reduces the risk of maintenance operations, and thus helps reduce the cost of energy. More importantly, this placement lowers the topside center of gravity which enables designers to meet platform stability and motions requirements using smaller and less costly platforms.

1.1 Objective

Sandia National Laboratories (SNL) is performing a feasibility study for a floating offshore vertical axis wind turbine (VAWT). In support of this study, SNL requested Stress Engineering Services Inc. (SES) to provide a design and associated cost analysis for a floating platform and mooring system specifically tailored for a VAWT. The purpose of this request was to increase and ensure confidence in the levelized cost of energy (LCOE) estimates performed by SNL.

1.2 Scope of Work

To meet the stated objective of this study, SES proposed a scope of work structured into two phases [1]: a concept screening study (Phase 1) followed by a down-select process leading to a single candidate to be chosen for further design work (Phase2). A description of the sub-phases for this scope of work is provided below.

- **Phase 1-A - Establish Design Conditions and Constraints for Platform and Mooring:** Through a series of conversations beginning with the project kick-off meeting, SNL and SES worked together to establish the design conditions and constraints for the platform and mooring system that would support the VAWT. These include: site location and metocean characteristics; VAWT system mass, inertia, center of gravity, and center of pressure; VAWT operational loads imposed on the floating platform; design load cases; vessel motion requirements and other metrics for quantitatively and qualitatively evaluating various platform and mooring design concepts.

- **Phase 1-B – Identify and Evaluate Platform and Mooring Concepts Tailored for a VAWT using Spreadsheet Calculations:** For this part of Phase 1, SES proposed six floating platform and mooring system concepts as candidates for design. First-principles calculations were performed to establish the fundamental performance characteristics of the proposed systems including system natural periods and estimated vessel rotations. A scorecard was developed listing the qualitative advantages and disadvantages of each candidate system. Preliminary costs were estimated for the fabrication, construction, transportation, and installation of each design. Jointly, SES and SNL evaluated and prioritized the candidate platform and mooring concepts based on the performance and cost data collected. From this evaluation, one platform and mooring concept was selected for further design effort in Phase 2.
- **Phase 2-A – Design of Selected Platform and Mooring System:** In this part of Phase 2, SES performed dynamic analysis using RAMS to produce a platform and mooring system design that satisfies the engineering performance criteria for two load cases: a maximum operating case and an extreme event case. VAWT operational loads were developed by SNL using SES-provided data describing the inertial, hydrodynamic, and stiffness properties of the floating foundation. Multiple iterations of design were employed to achieve a reasonable and final design of the platform and mooring system tailored to a VAWT.
- **Phase 2-B – Estimation of Costs and Documentation:** The level of design in Phase 2 was sufficient for estimating costs for the major categories of expenditure with an expected accuracy range of ~+/-20%. These estimates were based on historical cost data from one-of-a-kind deepwater floating oil and gas platforms for major oil companies. This report serves as the documentation for the design effort of both phases including the cost associated with the fabrication, commissioning, transportation, installation, and integrity management of the VAWT platform and mooring system design.

1.3 About Stress Engineering Services (SES)

Stress Engineering Services (SES) is an employee-owned engineering services company founded in 1972. As such, SES renders totally independent and unbiased engineering solutions and opinions. The company, which has office facilities and laboratories in Houston, Cincinnati, New Orleans, Canada, and Singapore, has a present staff of 400+ with engineers numbering 220+. Our engineers are highly trained with roughly 67% holding advanced degrees, and highly experienced with about 25% having more than 20 years of experience.

A leading provider of floating systems solutions for over 40 years, SES has extensive experience working with clients in the oil & gas industry on the development of offshore floating platform and mooring system design. SES' technical distinction and advanced software programs uniquely position it to successfully optimize the performance, reliability, and safety of floating systems.

At the core of SES' floating system analytical capability is its proprietary dynamic analysis program, RAMS (Rational Approach to Marine Systems). Unlike other analysis tools, RAMS performs fully coupled dynamic analysis of floating systems with the mooring and floating platform all connected in a single model. The capability of RAMS combined with its expertise in testing, mooring design/analysis, reliability, and materials uniquely positions SES to provide a comprehensive range of services.

A floating system is a complex assembly of platforms, moorings, controls, and instrumentation. In all phases, from feasibility through execution, it must be designed and treated as a system. SES operates from this system perspective, whether designing the individual parts or integrating them into a whole. SES is also highly qualified to perform the coupled analyses that are essential to making well-informed system decisions.

1.4 Acknowledgements

The technical monitor for this project is D. Todd Griffith, Sandia National Laboratories Wind Energy Technologies Department.

1.5 Abbreviated Terms

A glossary of abbreviated terms used in this document is provided in Table 3.

Table 3: Abbreviated Terms

Term	Definition
2P	Twice per revolution
4P	Four times per revolution
BM	Distance from center of buoyancy to vessel metacenter
CAPEX	Capital expenditures
GM	Distance from center of gravity to vessel metacenter
HAWT	Horizontal axis wind turbine
Hs	Significant wave height
KB	Distance from vessel keel to center of buoyancy
KG	Distance from vessel keel to center of gravity
KM	Distance from vessel keel to metacenter
McTLP	Multi-cellular Tension Leg Platform
MWL	Mean water line
OPEX	Operating expenditures
RAMS	Rational Approach to Marine Systems
SES	Stress Engineering Services, Inc.
SNL	Sandia National Laboratories
TLP	Tension Leg Platform
Tp	Peak wave period
VAWT	Vertical axis wind turbine

2. Design Basis

This section documents important design details and modeling choices relevant to the analysis and evaluation of the VAWT floating systems considered in this study. Specifically, this section provides:

- The rotor, drivetrain, and site description details specified by SNL [2, 3, 4];
- The VAWT maximum dynamic operating loads specified by SNL [5];
- The key drivers that shaped the down-select process from Phase 1 to Phase 2; and
- The software and analysis tools used in both Phase 1 and Phase 2 design analyses.

2.1 Rotor and Drivetrain Description

For this study, SNL selected a 5MW Darrieus turbine featuring two double-tapered blades made of carbon fiber composite material [2]. This turbine is depicted in Figure 2. The turbine is ~130 meters tall, with a ~100-meter working diameter, and is designed to operate in wind speeds ranging from 5 m/s to 25 m/s. A 10-m tower height extension raises the total height of the turbine to ~140 m. The total mass inclusive of the rotor, drivetrain, and associated equipment is 568,800 kg (1,254 kips) with a center of gravity 22.5 m above the base of the tower height extension. Additional details are provided in Table 4.

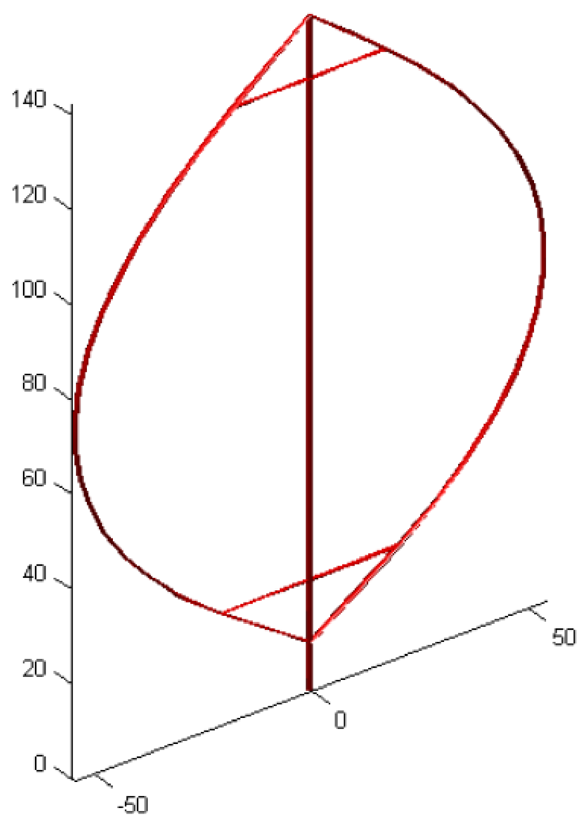


Figure 2: 5MW Darrieus Turbine

Table 4: Topside Properties Related to Rotor and Drivetrain

Parameter	Value			
Tower Height Extension	10	*m*	33	*ft*
Rotor Mass	220,800	*kg*	15,117	*slugs*
Drivetrain Mass	298,000	*kg*	20,403	*slugs*
Additional Mass (pumps, cabling, etc.)	50,000	*kg*	3,423	*slugs*
Total Topside Mass	568,800	*kg*	38,944	*slugs*
Distance from Base of Tower to Center of Gravity	22.5	*m*	74	*ft*
Mass Moment -- Yaw (about Base)	3.48E+07	*kg-m²*	2.56E+07	*slug-ft²*
Mass Moment -- Roll (about Base)	1.09E+09	*kg-m²*	8.03E+08	*slug-ft²*
Mass Moment -- Pitch (about Base)	1.13E+09	*kg-m²*	8.33E+08	*slug-ft²*
Mass Moment -- Yaw (about Center of Gravity)	3.48E+07	*kg-m²*	2.56E+07	*slug-ft²*
Mass Moment -- Roll (about Center of Gravity)	8.08E+08	*kg-m²*	5.95E+08	*slug-ft²*
Mass Moment -- Pitch (about Center of Gravity)	8.41E+08	*kg-m²*	6.20E+08	*slug-ft²*
Center of Pressure	76	*m*	249	*ft*
Cutout Max Thrust Load	1043	*kN*	234	*kips*
Cutout Mean Thrust Load	580	*kN*	130	*kips*
Overturning Moment at Cutout -- Max	79,300	*kN-m*	58,488	*kip-ft*
Overturning Moment at Cutout -- Mean	44,100	*kN-m*	32,526	*kip-ft*
Max Rotor Torque at 5.5 MW Rotor Power	7,290	*kN-m*	5,377	*kip-ft*
Max RPM	7.2	*rpm*	7.2	*rpm*
Number of Blades	2			
Turbine Type	Darrieus			
Chord Size	Large			
Taper at Blade Root	Double Taper			

Notes: Values for overturning moment and rotor torque were preliminary and only used in Phase 1 design. Please refer to Appendix H for the updated overturning moment and rotor torque values used in Phase 2 design

2.2 Site Description

For this study, SNL selected a representative site located off the northeastern coast of the United States approximately 25 km from port. The local bathymetry at this site ranges from 125 m to 165 m; however, for the purpose of this study, the VAWT floating systems considered at this site were evaluated for a single water depth of 150 m [2]. Due to the rising and lowering of tides, this site has a semi-diurnal water depth variation of 4 m [3]. This depth variation affects the freeboard criterion set for tension leg platforms.

2.3 Design Load Cases

The extreme event load case chosen for this study is an environment with a 50-year return period. This environment is characterized as having a significant wave height of 8.0 m, an associated peak wave period of 10.0 s, and an associated wind speed of 18 m/s [2].

For the maximum operating load case, no metocean data was formally prescribed. Therefore, a load case was created pairing the cutout wind speed of 25 m/s with an average annual environment characterized by a significant wave height of 1.07 m and an associated peak wave period of 7.49 s [4].

Table 5 summarizes the design load cases selected for this study. In addition to these load cases, the Phase 2 design candidate was checked for fundamental vessel stability during tow-out (i.e. positive GM).

Table 5: Design Load Cases

Parameter		Load Case	
Platform Condition		Operating	Extreme
Turbine Condition		Power Production	Parked
Wind Category		Cut-out	50-year
Wind	**10min @ top of turbine**	25 *m/s*	18 *m/s*
Wave	**Hs**	1.07 *m*	8.0 *m*
	Tp	7.49 *s*	10.0 *s*
	Gamma	1.0 --	1.0 --
Current	**Surface**	0.5 *m/s*	0.8 *m/s*
	40m depth	0.3 *m/s*	0.4 *m/s*
	150m depth	0.3 *m/s*	0.4 *m/s*

Notes: 1. The environment associated with the operating load case is hypothetical and was created for the purposes of this study. This environment pairs a maximum operating wind speed of 25 m/s with the average annual wave height of 1.07 m and wave period of 7.49 m [2].
2. Each wave environment is described by a JONSWAP spectrum.
3. Current profiles are estimated from site specific current data for 10-year return period [3].
4. For each load case, the direction headings for wave, wind, and current are assumed to be collinear.

Turbine loads associated with the operating load case are addressed in Section 4.2.

2.4 Key Design Considerations

Early on, several key design considerations were identified. The following design drivers helped to motivate and guide the design process.

- **Maximum Allowable Heel Angles:** In order to maximize the amount of energy captured by the VAWT during operating conditions, vessel heel angles should be kept to a minimum. For this study, the maximum allowable heel angle was specified to be ±10 deg [2].

- **Maximum Allowable Yaw Angles:** When operating, VAWTs impart a torque to the supporting vessel. Excessive yaw can reduce the relative motion between the rotor and generator, and thus reduce the amount of energy captured. For this study, the maximum allowable yaw angle was specified to be ±10 deg [2].
- **Vessel Array Spacing:** To take advantage of the energy capture potential for a given lease, vessel array spacing should be minimized. For this study, the spacing between nearest neighbor floating VAWTs was specified to be 800 m [2].
- **Vessel Freeboard:** In this study, the design freeboard is defined as the nominal vertical distance between the mean water surface and the bottom of the turbine blades. Based on this definition, the design freeboard was estimated based on the design storm significant wave height (8.0 m) and the semi-diurnal water depth variation (4 m). Thus, the design freeboard was determined to be 20 m for tension leg platforms and 15 m for all other vessel types.
- **System Natural Periods:** Clearly, a potential resonant response should be avoided in any floating system design. Therefore, the natural periods of each candidate floating system are checked against the 10-second peak period of the design wave spectrum as well as the periods associated with the twice per revolution (2P) and four times per revolution (4P) VAWT loads, which are 4.17 seconds and 2.08 seconds, respectively.
- **Amenability to Mass Production:** Because of efficiencies developed through supply chain and automation, mass production can potentially lead to a reduction in unit costs. For this study, an array 100 floating VAWTs is considered.
- **Quay-side integration and Tow-out Capability:** Removing the costs associated with an offshore integration of the topsides should produce significant savings. Therefore, the ability to tow-out the vessel with all the topsides (including rotor and drivetrain) fully-integrated is an economically attractive feature.

2.5 Software and Tools Used for Analysis

SES used the following programs to evaluate the technical performance of the candidate VAWT floating platform and mooring systems:

- **Excel** (spreadsheet and solver optimization routines used for Phase 1 vessel sizing and hydrostatics calculations; developed by Microsoft)
- **Patran** (pre-processing software for finite element analysis, providing solid modeling, meshing, analysis setup for multiple solvers; developed by MSC Software)
- **WAMIT™** (determination of hydrodynamic pressure loads on wetted portions of floating structures used for Phases 1 and 2; developed by MIT)
- **RAMS** (Frequency- and time-domain coupled analysis of mooring and floating platforms used for Phase 2; developed by SES)

3. Phase 1 Design

This section documents key aspects of the Phase 1 design effort. Specifically, this section describes:

- The six floating system concepts selected as candidates for Phase 1 design;
- The process for determining fundamental performance characteristics of these candidates;
- The preliminary cost estimates for each of these candidates; and
- The process for selecting one candidate for further design effort in Phase 2.

3.1 Design Concepts

At the start of the first design phase, SES surveyed more than fifty floating system concepts in search of promising candidates that could be tailored to support a 5MW VAWT. Many of the concepts that were under consideration have been catalogued in the floating offshore wind market and technology review published by the Carbon Trust [6]. During this survey, SES qualitatively evaluated the floating concepts according to the following criteria:

- Concepts are described in enough clarity to allow assessment with spreadsheets
- Field-proven hull/mooring performance
- Suitability to the unique loading from a VAWT
- Potential sensitivity to hydrodynamics
- Redundancy in mooring and vessel buoyancy
- Ability to tow-out with topsides fully installed
- Water depth scalability
- Potential sensitivity to fatigue
- Amenable to mass production
- Simplicity over complexity with robustness to survive in the open ocean
- Innovation which can lead to lower cost of electricity

Among the dozens of floating concepts considered, the following six were chosen for Phase 1 design:

- **Concept #1 - Four-column semi-submersible**: This semi-submersible floating concept has an extensive record of field-proven performance in the offshore oil and gas industry. This particular design concept consists of four corner columns, which are the primary source of the vessel's stability. The columns are tied together at the keel with four pontoons which consist of ballast compartments and provide damping to the motions. More importantly, the ability to tow-out with the turbine fully installed makes this an attractive concept.

- **Concept #2 - Classic spar**: This traditional deep-draft concept also has an extensive record of performance in the oil and gas industry. This spar column consists of three sections: the uppermost section (i.e. hard tank), which provides the necessary buoyancy to support the vessel; the midsection, which extends the outer shell of the hard tank downward (i.e. soft tank); and the bottommost section (i.e. fixed ballast tank), which contains the fixed ballast that is the primary source of the vessel's flotation stability. Because of its single-column design, the classic spar structure should be amenable to mass production. However, the main downside of the concept is its inability to float out with the turbine installed.

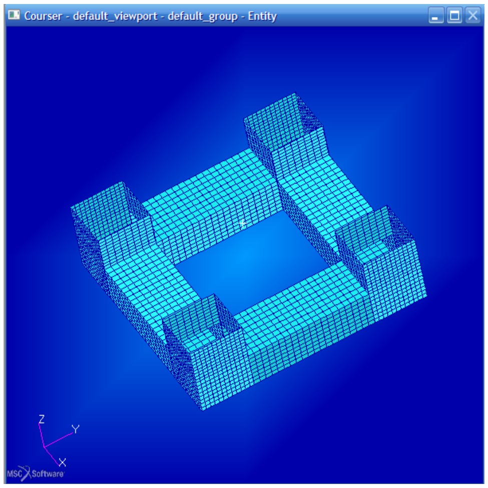
- **Concept #3 - Ring pontoon**: This novel variation of the barge concept was inspired by a design developed by IDEOL for floating HAWTs. The concept is simple: a semi-submerged pontoon ring with a fully-submerged skirt that extends horizontally from the vessel keel. The pontoon's water-plane area provides the vessel's flotation stability, while the skirt provides heave damping during large seastates. This concept also has the potential ability to tow-out with turbine fully installed.

- **Concept #4 - Compact semi-submersible**: This novel variant of the traditional semi-submersible concept was inspired by a design developed by Mitsui Engineering and Shipbuilding. This particular concept consists of a fully-submerged Y-pontoon structure which connects four large columns. The size and spread of the outer three columns are the primary source of the vessel's flotation stability. This concept offers the same potential benefits for mass production and tow-out capability as the more traditional four-column semi-submersible; however, its compact design may offer comparable performance with reduced material costs.

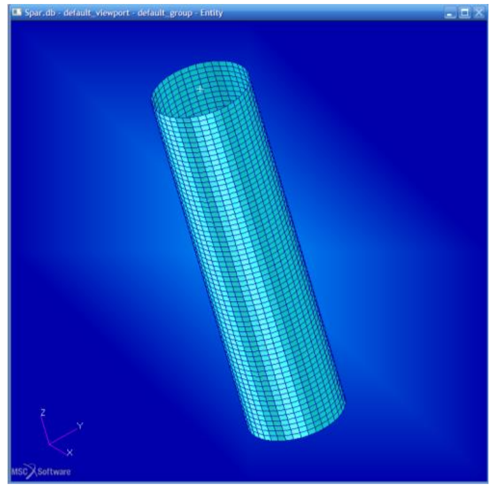
- **Concept #5 - Advanced spar**: This novel variant of the classic spar was inspired by a design developed by Japan Marine United. The advanced spar not only offers motion characteristics comparable to that of a classic spar, it also offers the possibility to tow-out with the turbine fully installed. This tow-out capability is due to the advanced spar's large diameter soft tank which can function as a pontoon that enables a vertical tow-out. The technology readiness level for this concept, however, is low.

- **Concept #6 - Multi-cellular tension leg platform (McTLP)**: TLPs have a considerable record of field-proven performance in the offshore oil and gas industry. Since TLPs are tendon-stabilized platforms, a TLP's motion characteristics are more strongly influenced by the stiffness and pretensions of the tendon system than they are by the hull form. Many hull forms are capable of providing the requisite buoyancy to support the vessel payload; however, the McTLP concept, inspired by a design by Petroneering, has unique multi-cellular design which lends itself to potential efficiencies and cost savings when mass produced. Equally important, the ability to tow-out the McTLP hull with the turbine fully installed makes this an attractive concept.

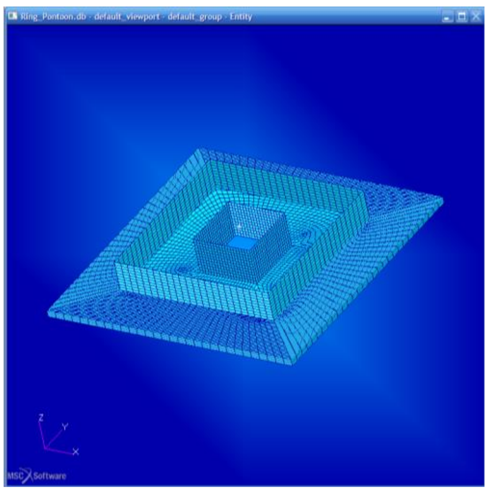
Renderings of each of these six hull forms are provided in Figure 3.



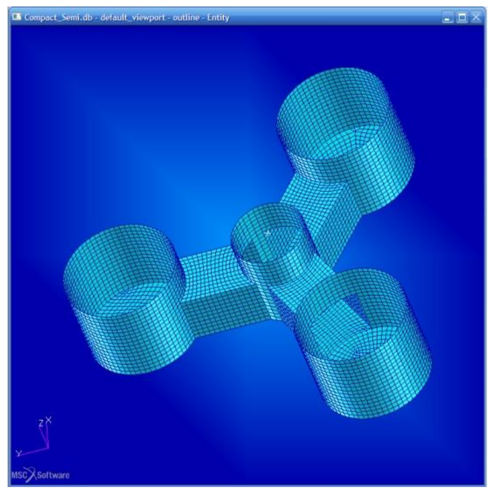
#1: Four-column Semi-submersible



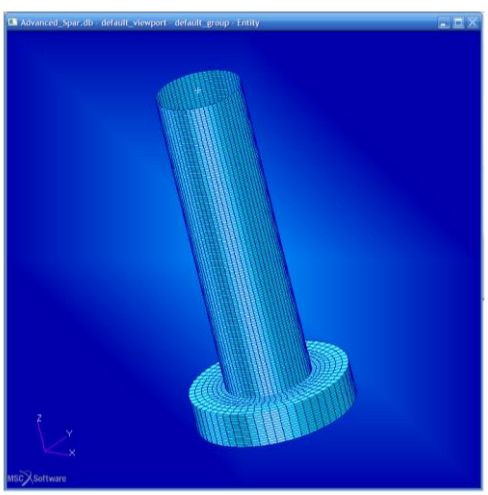
#2: Classic Spar



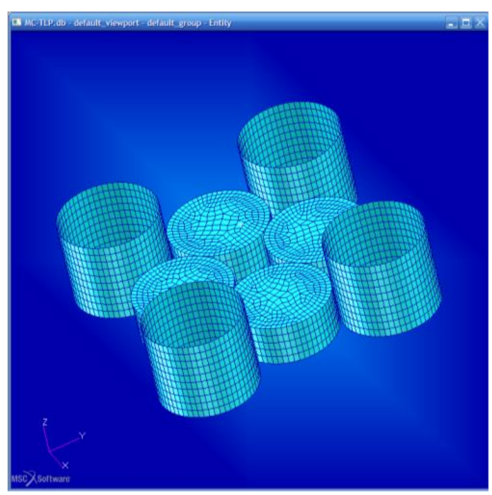
#3: Ring Pontoon



#4: Compact Semi-submersible



#5: Advanced Spar



#6: Multi-cellular Tension Leg Platform

Figure 3: Patran Models of Phase 1 Design Concepts

3.2 Design Process

For Phase 1, SES conducted a preliminary sizing study of the six selected floating system concepts in their operational configurations. First-principles calculations were performed to establish the fundamental performance characteristics of the proposed systems including system natural periods and estimated quasi-static vessel rotations. These calculations were achieved through a four-step iterative design process which is illustrated in Figure 4 and described in detail in the section below.

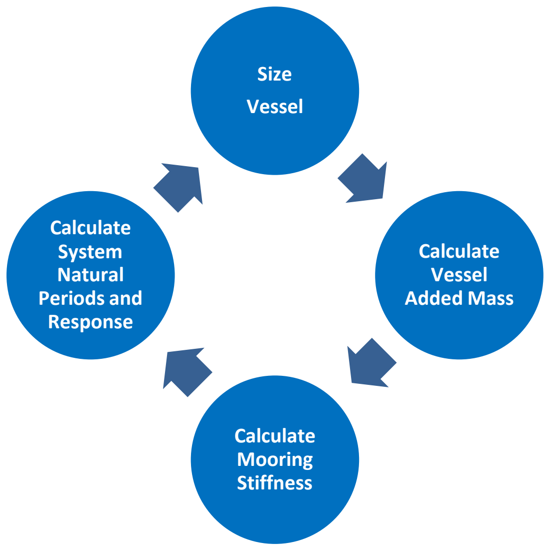


Figure 4: Phase 1 Design Process

- **Step #1 – Size Vessel**: To facilitate the vessel sizing process, each concept was streamlined so that the hull geometry could be expressed in terms of only a few essential dimensions. These essential hull dimensions along with other vessel particulars (e.g. operational draft, vertical mooring tension, water ballast, minimum freeboard, payload) were then entered into the concept-specific sizing spreadsheet. Based on this information, the vessel displacement, center of buoyancy, and the metacenter were calculated. Lightship weight was estimated based on the weight estimation rules published by Halkyard [7]. (SES independently determined that the estimated volumetric weights suggested by Halkyard are reasonable for the sizing of oil and gas platforms; however, to account for the fit for purpose specifications unique to offshore wind platforms, SES applied a factor that reduced these estimated volumetric weights.) After the vessel's lightship was estimated, the vessel's center of gravity and metacentric height were calculated. The Excel Solver Algorithm was then employed to target three primary vessel attributes:
    - Minimize Lightship Weight (to reduce the cost of steel)
    - Target Vessel GM (to ensure fundamental stability)
    - Target Tow Draft (not applicable to the Classic Spar concept)

- **Step #2 – Calculate Vessel Added Mass:** Closed-form solutions for determining added mass are available for only a few simple shapes. Thus, using WAMIT was decided to be the best way to determine the vessel added mass. To facilitate the rapid creation of WAMIT models over multiple design iterations, PATRAN scripts were developed based on the sizing inputs determined in Step #1. These PATRAN scripts were used to generate a finite element mesh of the immersed portion of each hull. This finite element model, along with a detailed estimate of the vessel mass matrix, was submitted to WAMIT to determine the vessel added mass at infinite wave period (i.e. quasi-static conditions). In addition to the added mass, WAMIT was used to calculate the vessel hydrostatic stiffness.

- **Step #3 – Calculate Mooring Stiffness:** SES proprietary software RAMS offered the fastest way to develop a mooring system model and evaluate its contribution to the global stiffness of the system. Key mooring parameters (e.g. number of lines, spread, component type, component length, cross-section, axial stiffness, and pretension) were used to generate a RAMS mooring model. RAMS was then used to calculate the contribution of the mooring system to the tangent stiffness of the global system in its nominal configuration. Finally, a sensitivity check on the mooring stiffness was performed by applying a static yaw moment equivalent to the estimated maximum VAWT rotor torque and verifying the resulting yaw displacement.

- **Step #4 – Calculate System Natural Periods and Estimate Vessel Response:** In order to calculate the natural periods of a given platform and mooring system: (1) the hull's hydrostatic stiffness from WAMIT was combined with the mooring stiffness from RAMS to generate the stiffness of the global system, and (2) the vessel mass matrix from Excel was combined with the vessel added mass from WAMIT to generate the mass matrix of the system. The system mass and stiffness matrices were then used to calculate the system natural periods in surge, sway, heave, roll, pitch, and yaw. These natural periods were then compared to the periods of the vessel loads, notably: 10 seconds, associated with the peak wave period for the 50-year environment; and 4.17 and 2.08 seconds, associated with the 2P and 4P VAWT harmonic loads, respectively. The maximum overturning moment at cutout was used to estimate the associated vessel roll/pitch rotation. The maximum rotor torque was used to estimate associated yaw displacement.

Steps #1 through #4 were repeated as necessary to achieve the desired system natural periods and estimated vessel motion characteristics.

Appendices A through F summarize the results reported during the Phase 1 design review of Concepts #1 through #6, respectively. Some concepts, specifically the four-column semi-submersible and the classic spar, required a second design pass in order to meet key design criteria. In the case of the four-column semi-submersible, several remediation techniques (i.e. heave plates, tapered columns, wider column spread) were used to improve the vessel heave, roll, and pitch characteristics. A deeper draft version of the classic spar was also developed to improve the vessel heave characteristics.

3.3 Cost Estimation

Upon completion of the Phase 1 design process, cost estimates were developed for each of the candidate floating systems. These estimated costs were based on historical cost data from one-of-a-kind deepwater floating oil and gas platforms for major oil companies.

Aspects that were considered when making these Phase 1 cost estimates are:

- **Construction of the Hull and Turbine Support Structures:** This cost category includes bulk materials; the labor and equipment associated with fabrication; project management, overhead, and profit; engineering; and certification.
- **Procurement and Fabrication of Mooring System:** This cost category includes the procurement of mooring lines (polyester rope, wire rope, and chain) and mooring line connectors (H-links, shackles, and ball grabs); as well as the materials for and fabrication of the anchor piles.
- **Tow-out of Floating Platform and Connection to Moorings:** This cost category includes the installation of the anchor piles and pre-lay of the mooring lines; the tow-out of the platform to the installation site; the connection of the platform to its mooring lines; the connection of the subsea transmission cable to the platform; the ballasting of the platform to its operating draft; the removal of any installation equipment; and the start-up of the VAWT.

Several aspects that were not considered when making these Phase 1 cost estimates are: pre-construction activities; the hook-up and commissioning of turbine system; any efficiencies derived from the mass production of 100 VAWT systems; inflation; and the available infrastructure or lack thereof.

Because the level of design at this point in the study was fairly preliminary, the expected accuracy range of these estimates was understandably large (greater than +/-20%). Nevertheless, these cost estimates were adequate for comparatively evaluating the candidate floating systems during the down-select process. Appendix G presents the estimated ranges of costs reported during the Phase 1 design review of Concepts #1 through #6.

3.4 Design Evaluation

To facilitate the down-select process, SES compiled several summaries which provide a direct comparison of the six candidate systems. Table 6 features a scorecard which highlights the qualitative advantages and disadvantages of each candidate with regard to several essential, preferred, and beneficial design features. Table 7 provides a quantitative summary of the performance characteristics (i.e. system natural periods, fundamental stability, etc.) and cost components (i.e. fabrication, construction, transportation, and installation) of each candidate. Additional comparisons were developed to evaluate the perceived trade-offs between key metrics, such as: the technical performance of a given concept vs. its potential to reduce capital expenditures (Figure 5); a concept's reliability or technical readiness level vs. its potential to reduce capital expenditures (Figure 6); and a concept's ability to minimize operating expenditures vs. its potential to reduce capital expenditures (Figure 7).

Based on these performance and cost summaries, SES and SNL jointly evaluated and prioritized the candidate platform and mooring concepts at the Phase 1 Design Review Meeting [8, 9]. From this evaluation, one platform and mooring concept was selected for further design effort in Phase 2. This section documents the rationale for this selection.

Of the six concepts, three (ring pontoon, compact semi-submersible, advanced spar) were quickly removed from consideration for Phase 2 design. The reasons for this decision are as follows:

- The ring pontoon was eliminated based on its low heave natural period and the difficulties associated with developing a cost effective remedy to this problem. Because it is a shallow-draft concept, the ring pontoon would require a considerably large skirt to capture the added mass needed to increase the heave natural period above the largest meaningful wave energy period, which is approximately 20 seconds. This concept would merit consideration if it were placed at a site with more benign seastates.
- The compact semi-submersible also exhibited a low heave natural period; however, SES was able to demonstrate with the four-column semi-submersible that there are several remediation techniques that can be employed to solve this problem. The challenge with the compact semi-submersible comes with its lack of redundancy in its column and mooring structure. Also, it ranks among the two most costly concepts to fabricate and install.
- Although a truly novel concept with good performance characteristics in operation, the advanced spar was removed from consideration based on its low technology readiness level (TRL) and concerns associated with its ability to be deployed with the topsides fully-assembled.

The three remaining candidates (four-column semi-submersible, classic spar, McTLP) each have their individual strengths with regard to technical performance and cost considerations. However, of these remaining concepts, SES and SNL decided that the McTLP offers the best combination of performance and cost to select it for Phase 2 design. Among the McTLP's key features are:

- **Ability to Tow-out with Turbine Fully-integrated:** In terms of cost and risk minimization, a quayside integration of the VAWT to the floating platform is preferable to an offshore integration at the installation site. Both the McTLP and four-column semi-submersible offer the possibility of quayside integration. The classic spar concept, however, would require a two-phase installation process (i.e. wet-tow and upend spar hull; float-over and integrate VAWT to hull.)
- **Small Pitch-Roll Motions:** SNL has demonstrated that wind energy capture diminishes with increasing pitch-roll motions [2]. Therefore, a vessel which exhibits small pitch-roll motions is preferable because it maximizes the energy captured. Of the concepts considered in Phase 1, the McTLP features the smallest pitch-roll motions. The classic spar and four-column semi-submersible, however, exhibit larger pitch-roll motions. Additionally, the McTLP's small pitch-roll motions should help reduce fatigue accumulation in the rotor shaft.

- **Multi-cellular Structure is Amenable to Mass Production**: All Phase 1 hull concepts feature compartmentalization which could simplify the fabrication and assembly process; however, the McTLP displays the largest potential to reduce capital expenditure costs via mass production. SES believes there should be some potential for further material and manufacturing cost reduction, as the design is further refined and optimized.

- **Lower Fabrication and Installation Costs**: The McTLP has several advantages over the semi-submersible that could lead to lower fabrication and installation costs. The McTLP's cylinders and pontoons are connected via vertical and horizontal steel shear plates welded to the outside of the columns and inner cells. These connectors would need to be evaluated for the unique fatigue considerations presented by an operating VAWT; however, they offer a potential reduction in fabrication costs when compared to the heavily stiffened moment connections required for semi-submersibles and conventional TLPs. For semi-submersibles, taut catenary moorings become more demanding as the water depth decreases (i.e., the anchor piles have to be sized to resist the higher horizontal forces which may require heavier piles and potentially higher capacity installation vessels). A TLP's tendon system does not encounter this challenge with decreasing water depth. Also, the McTLP's wire-rope tendons are not as complex as a semi-submersible's three-segment (chain, wire-rope, chain) mooring lines, which could potentially lead to comparatively lower fabrication costs and fewer fatigue critical points. Furthermore, the semi-submersible's mooring would need to be pre-layed on the seafloor, thus requiring additional time and equipment that a TLP's tendon system would not require. Finally, of all the concepts considered in Phase 1, the McTLP offers the smallest mooring footprint, which simplifies the seafloor layout and enables a more compact field arrangement.

- **Static Ballasting System:** The McTLP features a ballasting system that is intended to be static (during unmanned operations); however, the system can be adjusted by moving ballast internally during operation, if required. The ballasting system is assumed to be an air over water system that operates via air pressure. Initial tow-out would have little to no ballast to minimize the quayside draft. Once the tow reaches a sufficient water depth, the platform would be ballasted down to near operating draft, for stability purposes. During installation the ballast may need to be adjusted slightly to assist with tendon hook-up. After tendon hook-up the ballast would be reduced to set operating mooring tensions. It is assumed that a ballast monitoring system would be installed and monitored (similar to SES' NeoSight), with remote operation via wireless technology, although a manned ballasting operation would also be possible.

At the conclusion of the Phase 1 Design Review Meeting, SNL and SES jointly decided to move forward with the multi-cellular tension leg platform (McTLP) as the primary option for Phase 2 design. The classic spar was selected as a secondary option for Phase 2 design in the event the McTLP proved not to be a viable concept for a floating offshore VAWT.

Table 6: Phase 1 Design Concept Qualitative Comparison

Platform Design Features	Design Feature Categories				Phase 1 Design Concepts						Comments
	Tech	Capex	Opex	Reli-ability	#1 Four-column Semi	#2 Classic Spar	#3 Ring Pontoon	#4 Compact Semi	#5 Advanced Spar	#6 Multi-cellular TLP	
Essential Design Features											
Less than 1 G lateral acceleration	X						-				Quantitative analysis required but #3 has large wave zone area
Quasi-Static Rotor Torque Compatibility	X										Quantitative analysis required to decide compatibility
Dynamic Rotor Compatibility in torque, pitch, and roll	X										Quantitative analysis required to decide compatibility
Anchor Pile Spacing Less than 800m	X									+	Quantitative analysis required but #6 anchors are less than 800m
Float Out Complete/Dry Dock for Blade Repair		X	X		+	-	+	+		+	Unsure if #5 can tow vertically, #2 has separate hull & deck tows
Amenable to Mass Production		X				+			+	+	Based on multiple pieces of same size and shape
Mooring Line Redundancy				X							This should be made a part of design requirements
Preferred Design Features											
Minimize Hull Fabrication/Assembly		X				+			-		#2 assembled low to ground, #5 requires high crane lifts
Minimize Hull Special Materials/Equipment		X								+	No mechanical fairleads required for #6
Minimize Hull Marine Systems & Outfitting		X	X			+	-		+		#1,#4 require most compartmentation, #3 may need double hull
Minimize Above Water Deck and Hull Steel		X				+			+		#2,#5 have but single column above water and compact deck
Minimize Mooring Line Material/Anchor		X								+	#6 uses wire rope for tendons and requires minimal lengths
Minimize Mooring Line Pre-Install/Hook-up		X								+	#6 wire rope tendons are pre-rigged on hull
Minimize Hull Installation		X				-					#2 requires upending operation, fixed ballast and deck installation
Minimize Mooring Line Replacement			X							+	#6 wire rope tendons can be replaced using ROV assist
Minimize Hull/Mooring Structural IM			X			+					#2 has fewest compartments to inspect
Minimize Decommissioning			X			-			-		#2 will require reverse upending, #5 will require re-floating
Beneficial Design Features											
Scalable to Larger Turbines		X									Similar study required to check multiple size turbines
Water Depth Scalability		X									Similar study required to check multiple water depths
Field Proven Hull/Mooring Performance				X	+	+	-		-		#1,#2,#4 have been used in oil and gas industry
Ease of Generator Removal/Replacement			X			+			+		#2,#5 provides closest work barge access for field generator replacement
Minimize Offset/Motions for Power Cable Design		X	X	X			-				Quantitative analysis required but #3 has large wave zone area
Minimize Drive Train Housing Wave Reinforcement		X	X	X		+					#2 float over deck is at highest elevation; See Appendix J for details

Key: + = relative advantage
- = relative disadvantage

Table 7: Phase 1 Design Concept Quantitative Comparison

Performance and Cost Details			Phase 1 Design Concepts					
			#1 Four-column Semi	#2 Classic Spar	#3 Ring Pontoon	#4 Compact Semi	#5 Advanced Spar	#6 Multi-cellular TLP
Design Iteration		--	2	2	1	1	1	1
Vessel Width at Keel		*m*	37	12	44	37	32	32
Vessel Draft		*m*	10	100	6	11	50	10
Displaced Volume		*m^3*	5,858	11,310	5,038	4,726	15,200	6,174
Displacement		*kN*	58,895	113,699	50,649	47,511	152,808	62,069
KB		*m*	3.6	50	2.4	5.0	20	4.1
BM		*m*	7.6	0.090	9.2	8.3	0.283	9.2
KM		*m*	11	50	12	13	20	13
KG		*m*	7.6	43	7.5	9.4	18	8.9
GM		*m*	3.6	7.3	4.1	4.0	2.5	4.3
Lightship Weight		*kN*	32,706	40,721	33,099	29,705	46,528	38,069
Vertical Mooring Tension		*kN*	270	270	270	270	270	24,000
Water Ballast		*kN*	25,919	6,322	17,280	17,536	3,521	0
Entrained Water		*kN*	--	66,386	--	--	102,489	--
Total Supported Weight		*kN*	58,895	113,700	50,649	47,511	152,808	62,069
System Natural Periods	**Surge**	*sec*	53.8	36.9	50.9	46.1	96.4	42.4
	Sway	*sec*	53.8	36.9	50.9	46.1	96.4	42.4
	Heave	*sec*	19.4	22.5	14.2	9.1	20.9	2.7
	Roll	*sec*	25.1	32.5	31.4	18.8	63.1	2.6
	Pitch	*sec*	25.1	32.5	31.5	19.0	63.2	2.6
	Yaw	*sec*	38.5	18.4	24.4	23.3	17.5	29.1
Estimated Fabrication Cost		*MM USD*	27 - 36	21 - 34	31 - 42	28 - 42	23 - 37	26 - 36
Estimated Mooring Cost		*MM USD*	4.1 - 5.2	4.1 - 5.2	4.1 - 5.2	4.1 - 5.2	4.1 - 5.2	2.1 - 2.8
Estimated Installation Cost		*MM USD*	5.8 - 8.1	6.8 - 10.0	5.8 - 8.1	5.8 - 8.1	7.0 - 9.9	4.3 - 6.2
Estimated Total Cost		*MM USD*	37 - 50	32 - 50	41 - 55	39 - 55	34 - 53	33 - 46

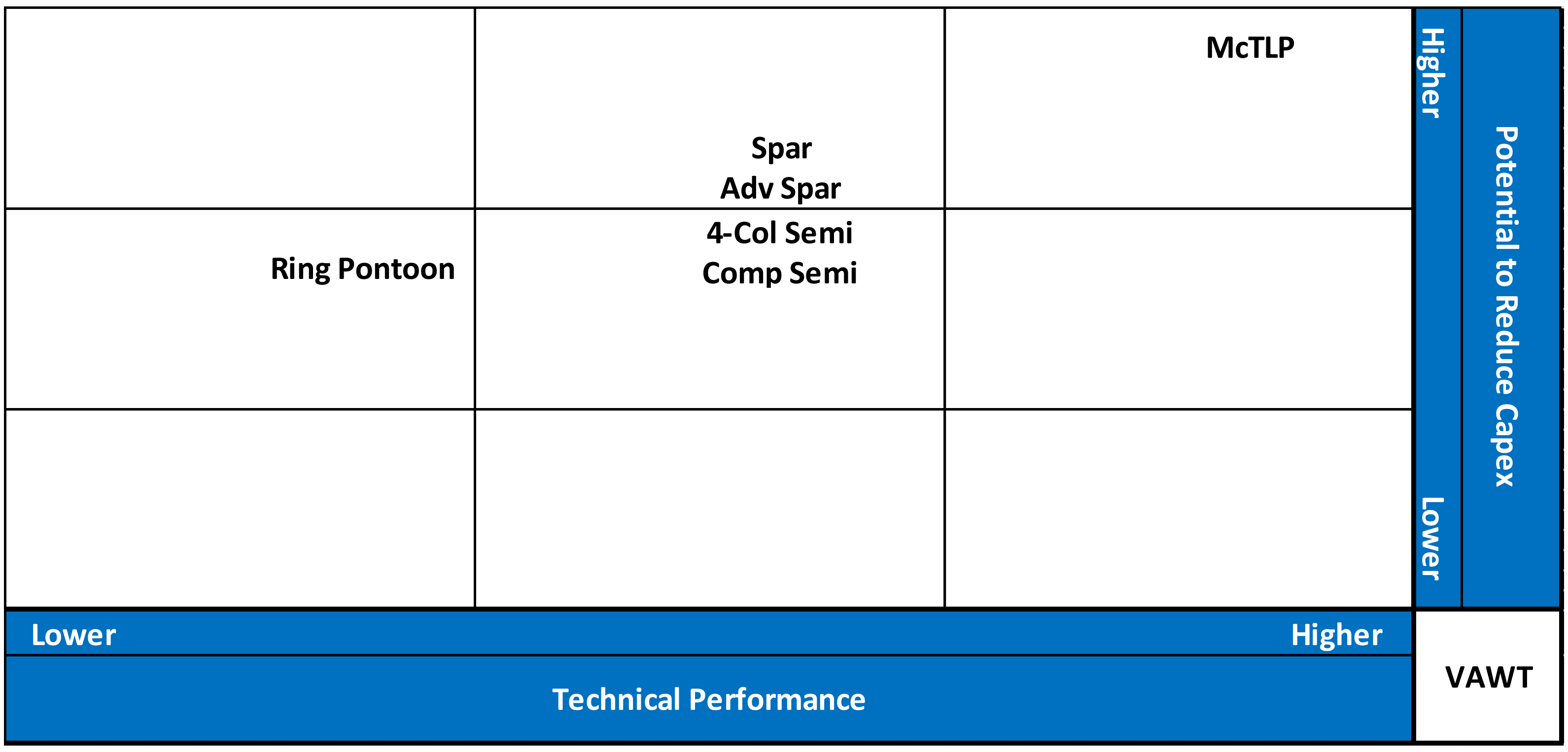


Figure 5: Technical Performance vs. Potential to Reduce Capex

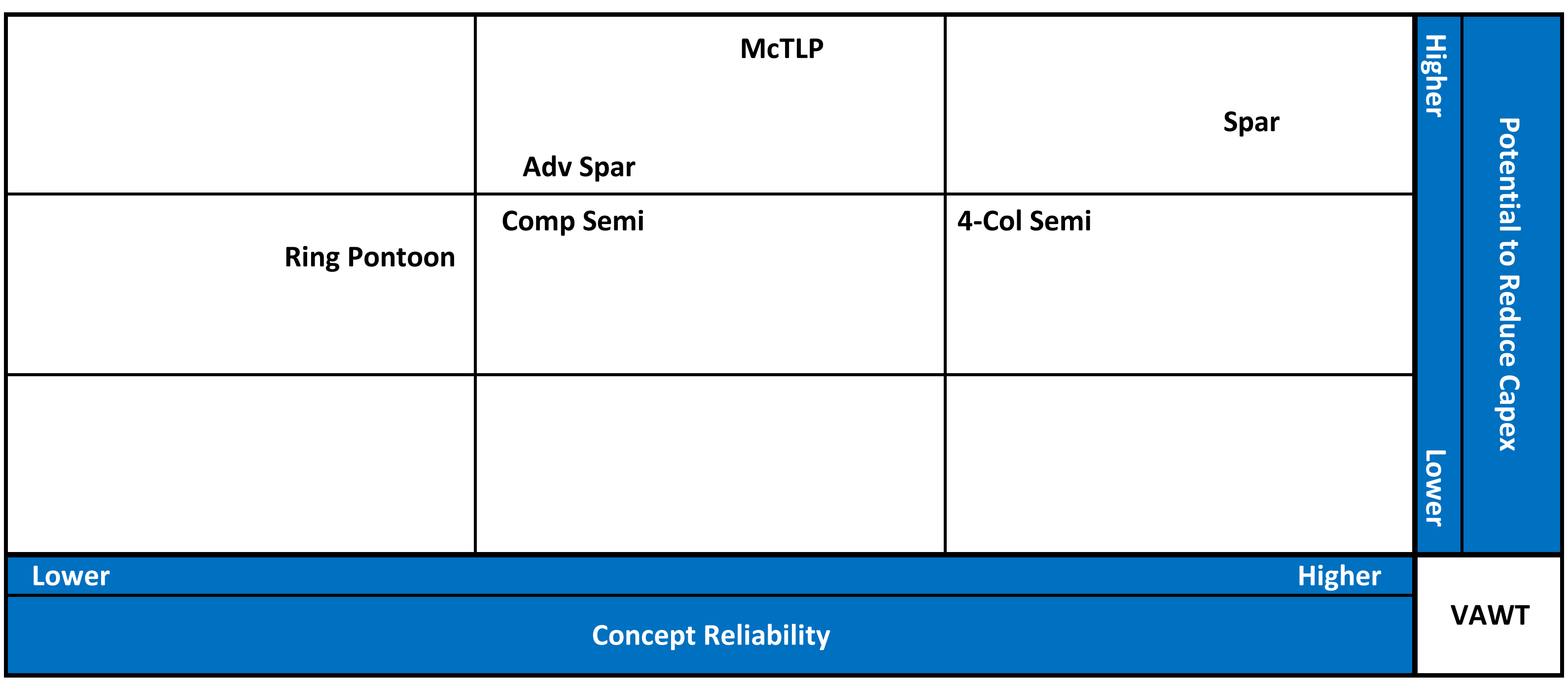


Figure 6: Concept Reliability vs. Potential to Reduce Capex

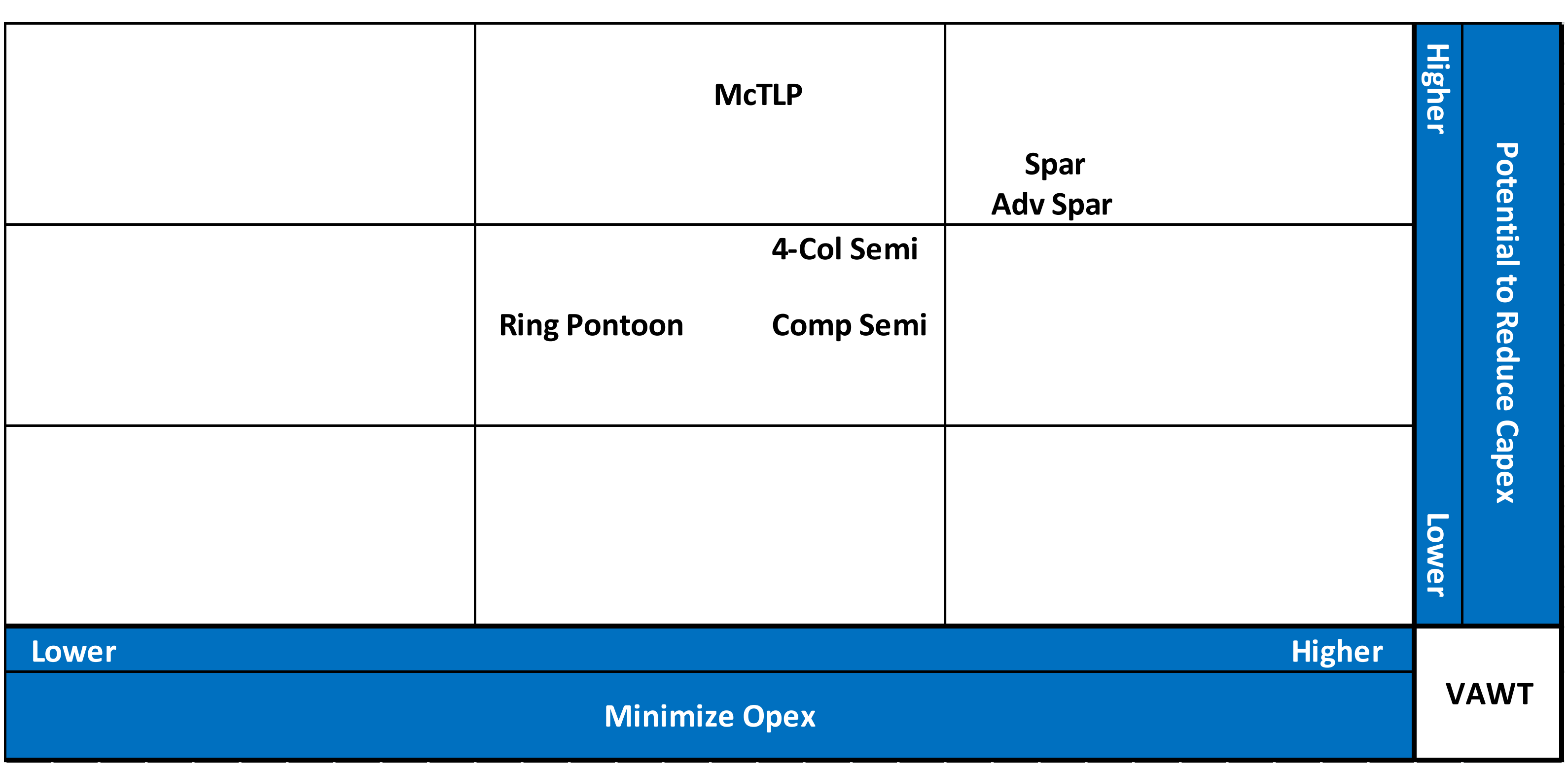


Figure 7: Minimizing Opex vs. Potential to Reduce Capex

4. Phase 2 Design

This section documents key aspects of the Phase 2 design effort. Specifically, this section describes:

- The RAMS global performance model of the McTLP for Phase 2 design;
- The VAWT dynamic loads used in the maximum operating load case;
- The process for reaching the final Phase 2 McTLP design; and
- The cost estimates for the final Phase 2 McTLP design.

4.1 Global Performance Model

For each design iteration in Phase 2, a global performance model was developed using SES' proprietary software RAMS. The RAMS coordinate system for each McTLP floating system is shown in Figure 8. The origin of this right-handed coordinate system is located on the mean water line at the point that aligns vertically with the platform's geometric center. Vessel surge, sway, and heave align with x-, y-, and z-axes, respectively. Wind, wave, and current directions are specified as the direction toward which the environment is headed as measured counter-clockwise from the positive x-axis.

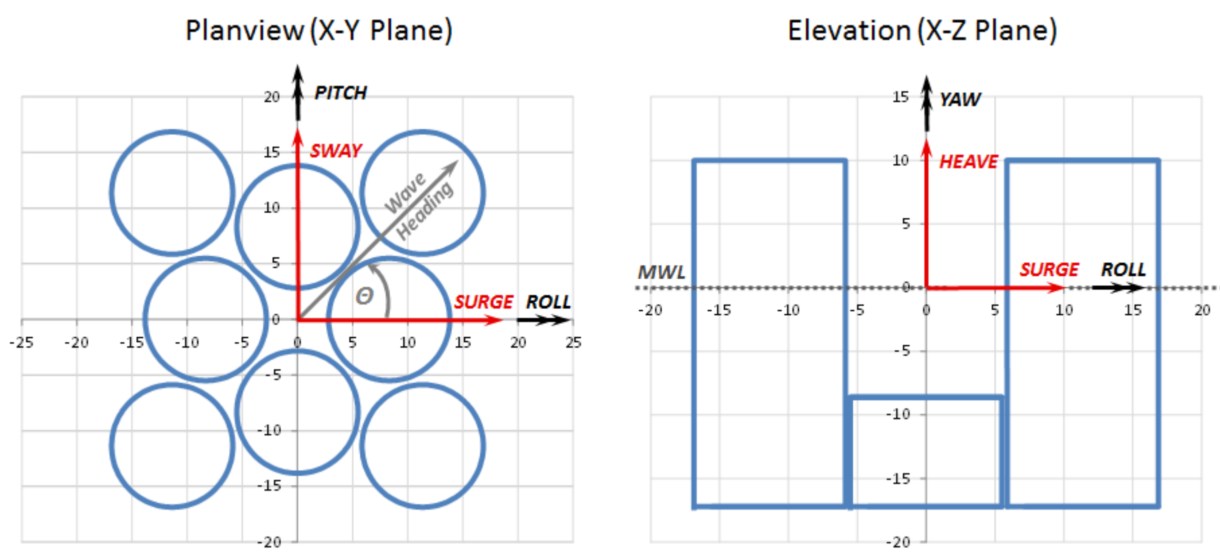


Figure 8: Coordinate System for Global Performance Model

One rigid body element, located at the mean water line, was used to represent the McTLP platform (i.e., hull and topsides, inclusive of all decking, turbine, drivetrain, etc.). This rigid body, which was attributed with the inertial and hydrodynamic properties of the McTLP platform, provided the point of application for all environmental loads. A second rigid body, located 10 m above the first rigid body, was used to represent the base of the VAWT tower extension. This second rigid body was massless and provided a point of application for the VAWT operating loads supplied by SNL. Both rigid bodies were connected to each other via four rod elements, which were both rigid and massless. Tendons were modeled using slender elastic rod elements ascribed with an appropriate set of stiffness, weight, and hydrodynamic properties for wire rope. Hydrodynamic drag on the vessel was modeled using Morison-type elements to represent the wetted hull. Wave loads, including low frequency drift loads, were described using diffraction theory. Wind coefficients were developed to model static wind loads on the vessel deck and the rotor in the parked condition. Modeling inputs for these RAMS analyses are located in Appendix F.

4.2 Turbine Loads

Maximum dynamic operating loads for the two-bladed Darrieus turbine were calculated by SNL using their coupled wind and wave model of the floating VAWT system. This model used information provided by SES [10] to define the hydrostatic and hydrodynamic characteristics of the McTLP hull as well as the stiffness characteristics of the tendon system. In their analysis, SNL calculated the maximum operating loads imparted by the rotor to the platform at the base of the tower extension located 10 m above the mean water line. These loads, which were provided to SES in the form of a time series for each of the vessel's six degrees of freedom [5], are given in Appendix H. These maximum operating loads were evaluated for a single environment direction heading of 0 deg, which corresponds with the vessel surge direction.

SES performed a fast Fourier transform (FFT) of these time series in order to implement these operating loads into their frequency domain analysis. From this transformation, only two frequencies contribute significantly to loading spectra: 0.24 Hz which is the 2P forcing frequency and 0.48 Hz which is the 4P forcing frequency. These correspond to the 2P and 4P forcing periods of 4.17 seconds and 2.08 seconds, respectively. Except for heave, the 2P load contributions influence all vessel degrees of freedom. The 4P load contributions are only significant in yaw. Fourier coefficients used in the frequency domain modeling of the VAWT operating load are also provided in Appendix H.

4.3 Dynamic Analysis

For the Phase 2 design effort, SES further developed the McTLP platform and mooring concept through a series of hydrodynamic motions response analyses using the SES proprietary software RAMS. Dynamic analysis of each RAMS model was performed in the frequency domain for the two load cases described in Section 2.3: a non-operating extreme event load case with a 50-year return period and a maximum operating load case with turbine loading provided by SNL.

For this study, SES performed four design iterations to arrive at a reasonably sized platform and mooring system that meets the performance metrics set by SES and SNL. These design iterations are summarized in Table 8 and described in detail in the section below.

Table 8: Phase 2 Design Iteration Summary

Design Iteration	Cell Diameter m	Vessel Draft m	Lightship Weight N	Tendon Diameter mm	Tendon Tension N	Reason for Next Design Iteration
1	11.6	10.0	38,069	114	3000	Tendons slack during 50-yr event Draft too shallow
2	10.0	17.2	29,510	153	3000	Instability when ballasting down Columns are too slender
3	11.0	17.2	34,148	153	3000	Tendons slack in operational case Tendon pretensions too low
4	11.0	17.2	34,148	153	3500	n/a

- **Iteration #1:** This design iteration evaluated the McTLP design that was sized at the end of Phase 1. Extreme event analysis of this design was performed for three environment headings (0, 22.5, and 45 deg). For the 0-deg environment, this analysis yielded negative minimum tendon tension for all eight tendons. It was determined that the vessel draft of this design (10 m) was too shallow, and that wave energy from the 50-year environment was imparting loads to the vessel's keel. To remedy this problem, a deeper draft McTLP hull was designed and the tendon size was increased from 114 mm (4.5 in) to 153 mm (6 in).

- **Iteration #2:** Analysis of the new deeper draft design (17.2 m) was performed for the same load cases and environment headings analyzed in Iteration #1. Results from these analyses demonstrated that minimum tendon tensions were improved but still not acceptable. Additionally, in searching for an appropriate tow-draft for this vessel, it was determined that this deeper draft design experiences a stability problem the moment when the pontoons are fully submerged. The immediate drop in the vessel's waterplane area causes the vessel GM to be slightly less than zero. This stability measure does not improve even as the vessel is ballasted downward. This problem exists because the ballast tanks in the four columns are too slender; therefore, the ballast quickly contributes to raising the vessel KG. Remedies such as installing fixed ballast (iron ore) and placing ballast tanks in the pontoons were considered. In the end, the McTLP was resized by increasing the diameter of the cells from 10 m to 11 m.

- **Iteration #3:** The increased cell size (11 m) allowed the vessel GM to remain positive throughout ballasting operations. Extreme and operational event analyses of this larger cell design were performed for the same load cases and environment directions evaluated in Iterations #1 and #2. Only the operational load case yielded negative minimum tendon tensions for a couple of tendons. To remedy this problem, the tendon pretensions were increased from 3000 N per line to 3500 N per line.

- **Iteration #4:** By increasing the installed tendon tensions to 3500 N per line, minimum tendon tensions during the operational load case improved to acceptable levels. The resolution of this problem concluded the Phase 2 design of the McTLP.

A rendering of the Patran model used in the hydrodynamic analysis of this McTLP hull is provided in Figure 9. The particulars associated with this final Phase 2 design are summarized in Table 9.

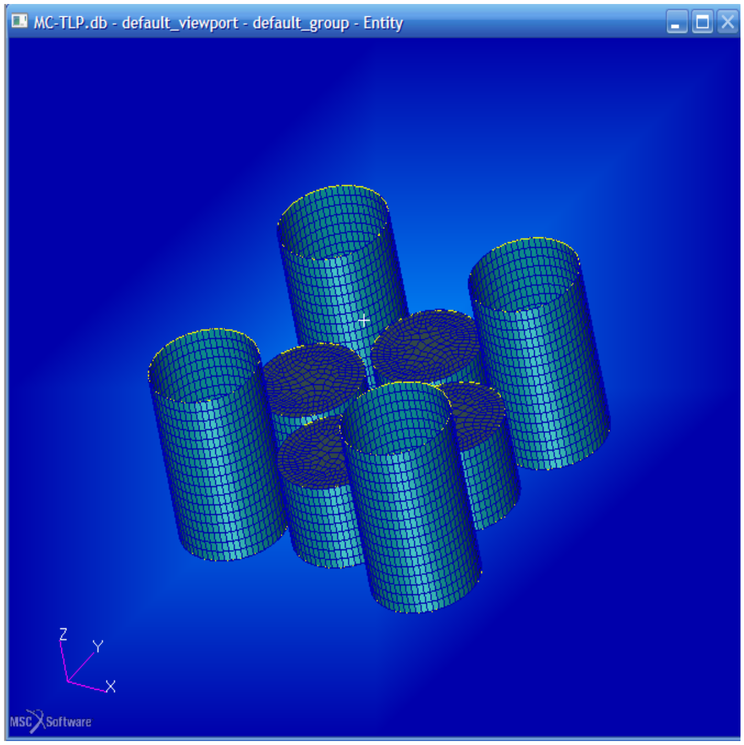


Figure 9: Patran Model McTLP Hull

Table 9: McTLP 5MW VAWT Platform Particulars

Parameter		Value			
Displacement		98,627	*kN*	22,172	*kips*
Operational Draft		17.2	*m*	56	*ft*
Vessel Span		33.7	*m*	111	*ft*
Pontoon Cell Diameter		11	*m*	36	*ft*
Pontoon Height		8.6	*m*	28	*ft*
Column Cell Diameter		11	*m*	36	*ft*
Column Height		27	*m*	89	*ft*
Freeboard		20	*m*	66	*ft*
Turbine Height (above mean water line)		150	*m*	492	*ft*
Lightship		34,148	*kN*	7,677	*kips*
Tendon Tension (individual line)		3,500	*kN*	787	*kips*
Tendon Tension (total for all 8 lines)		28,000	*kN*	6,296	*kips*
Water Ballast		36,478	*kN*	8,201	*kips*
Distance from Keel to Center of Gravity	***KG***	8.4	*m*	28	*ft*
Distance from Center of Gravity to Metacenter	***GM***	4.0	*m*	13	*ft*

4.4 Cost Estimation

Upon completion of the Phase 2 design process, cost estimates were developed for the final McTLP design. These cost estimates were based on historical cost data from one-of-a-kind deepwater floating oil and gas platforms for major oil companies. The data consisted of three components:

- **Fabrication:** The fabrication data included hull and mooring project management, engineering, overhead, profit, and certification. This data took the form of costs per unit hull weight. The costs per unit hull weight were applied to the spreadsheet weights to obtain the hull fabrication costs. Since the historical costs reflected a high level of specifications, typical of major oil companies, a reduction factor was applied to these costs to enable a lower bound which could be obtained via use of more industry wide specifications, particularly since the VAWT platforms will be unmanned.
- **Moorings:** The mooring costs were estimated in similar fashion except that the mooring line costs were estimated on the basis of water depth, to reflect the much shallower depth of the VAWT platforms. Factors were applied to reflect the potential for bridge industry connections to be used versus some customization which may be needed during final design. The factors also allow for some uncertainty in geotechnical information at this time.
- **Installation:** The installation costs were based on typical day rates and reasonable estimates of vessel types and number of days required to potentially execute the field operations. Cost factors were applied to reflect the volatility in installation vessel costs due primarily to vessel availability at any given time. It should be noted that no derrick barge costs were included due to the assumption that none will be needed for the VAWT platforms.

In Phase 1, efforts were focused on evaluating the differences between the various concepts, and cost estimates were based solely on costs associated with analogue deepwater oil and gas platforms. In Phase 2, however, efforts were focused on optimizing the McTLP within the bounds of the analysis capabilities used in this study, and cost estimates were developed to include some of the beneficial effects of economies of scale and the potential to use fit for purpose specifications (e.g., lowered risked due to unmanned operations; the ability for quayside in lieu of offshore inspection and repair). To account for these beneficial effects, a factor was applied to the fabrication costs to reflect a volume discount anticipated from such a large steel order, as well as the efficiency which should be gained by producing 100 units. Additionally, the engineering and certification costs were divided by 100, since they do not need to be repeated for each identical VAWT platform. Likewise, the anchor handling vessel mobilization cost was divided by 100, assuming the vessels would work continuously. No weather downtime was specifically included, as it should be included in the day rates.

A summary of the estimated costs associated with the fabrication and construction of the McTLP hull and mooring system (excluding the turbine, drivetrain, and ancillary equipment), as well as the transportation and installation of the fully-integrated turbine-hull-mooring system is provided in Table 10 and Figure 10. The long-form versions of these cost estimates, which were submitted to SNL [11], are located in Appendix I.

Based on the level of design definition achieved at the end of Phase 2, these cost estimates can be considered Class 3 estimates in terms of the system published by AACE International [12]. The expected accuracy range of these estimates is ~+/-20%.

Table 10: Summary of Estimated Costs for 5MW VAWT McTLP

Item	Lower Bound Cost	Upper Bound Cost
Project Costs	2.0 *MM USD*	2.7 *MM USD*
Turbine Support Structure	1.0 *MM USD*	1.3 *MM USD*
Interior Columns	3.6 *MM USD*	5.0 *MM USD*
Outer Columns	11.5 *MM USD*	15.9 *MM USD*
Hull Subtotal	**18.1** ***MM USD***	**24.9** ***MM USD***
Tendon Assemblies	0.9 *MM USD*	1.2 *MM USD*
Templates/Piles	1.3 *MM USD*	1.7 *MM USD*
Tendon System Subtotal	**2.2** ***MM USD***	**2.9** ***MM USD***
Installation Subtotal	**4.2** ***MM USD***	**6.3** ***MM USD***
GRAND TOTAL	**24.5** ***MM USD***	**34.0** ***MM USD***

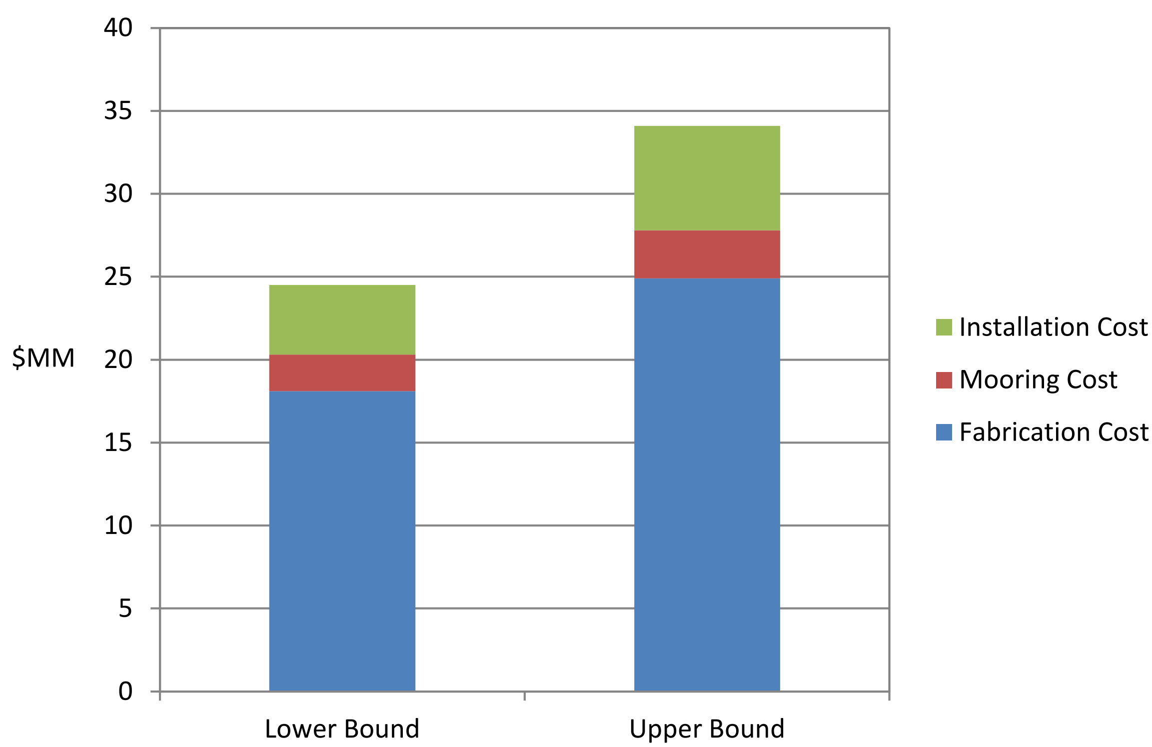


Figure 10: Estimated Costs for 5MW VAWT McTLP

5. Future Study

During the course of this project, multiple opportunities for future study have been identified. This section describes the opportunities that pertain to design development and cost savings.

5.1 Design Development Opportunities

It was outside of the scope of work for this project to quantify the scalability of the McTLP concept to other operational scenarios (e.g. three-bladed systems, larger MW turbines, different water depth). Exploring these scenarios with further design analysis is one opportunity that merits consideration. In qualitative terms, the McTLP is a versatile concept that should capably translate over the range of water depths being considered for offshore wind applications. Tendon sizing and pretensions may require some reconsideration for larger water depths. Alterations to the topsides weight must be considered in light of their effect on the vessel's GM. Fundamental stability will be compromised when additional weight greatly increases the vessel's center of gravity. This means that given the current size and design of the McTLP, a two-bladed fiber glass VAWT with a 5MW rating would not be advisable. A larger MW carbon fiber composite turbine or a heavier drivetrain, however, may be feasible. Again, further quantitative analysis will be able to address these issues with a high degree of confidence.

Other opportunities for future design development include: developing better metocean criteria for design analysis; developing additional load cases to assess the robustness of the design over a range of operational scenarios; advanced stability analysis of the free-floating McTLP; fatigue evaluation of the tendon system as well as vertical and horizontal shear plates which hold the cell columns and pontoons together; design of turbine support structure-to quantify weight further; preliminary scantling design to quantify weight and obtain order of magnitude estimates from potential shipyards; a northeastern U.S. shipyard assessment for potential construction sites to determine available infrastructure; and a fabrication methodology study, including VAWT installation and tow out.

5.2 Cost Saving Opportunities

If the development of the McTLP concept continues for this offshore wind application, there should be any number of opportunities to be explored which can possibly net further hull and mooring cost reductions. Some of these savings have been included in the cost estimate and can be quantified with further progress towards an actual project. Others include such things as: highly automated fabrication, which can take advantage of the simple cellular components and their stackable assembly method; investment in installation equipment which can be used continuously over a long time period to install anchor piles and pre-lay cable, as well as towing and connecting tendons; utilizing existing fabrication infrastructure to obtain competitive contracting scenarios. The small footprint of this particular hull and mooring concept should minimize farm acreage costs, cable and cable laying costs, as well as geotechnical surveying costs.

6. References

1. "Platform and Mooring System Design for a Vertical Axis Wind Turbine (VAWT): Technical Proposal," Stress Engineering Services, SES Doc. No. 1102668-EN-PQ-0002 (Rev. 0), April 21, 2015.

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3. "Current speed analysis at a VAWT site Final.pptx," provided via attachment to email from Todd Griffith (SNL) to Chad Searcy (SES) dated February 11, 2016.

4. "WaveSumm184262.pdf," (WaveWatch3 Hindcast distributions) provided via attachment to email from Todd Griffith (SNL) to Chad Searcy (SES) dated September 30, 2015.

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6. "Floating Offshore Wind: Market and Technology Review," Carbon Trust, June 2015.

7. "Design and Analysis of Floating Structures," John Halkyard, Third Edition, Version 2B, 2013.

8. "Platform and Mooring System Design for a Vertical Axis Wind Turbine (VAWT) Phase 1 Design Review," Stress Engineering Services, SES Doc. No. 1102668-EN-PT-0001 (Rev. B), March 15, 2016.

9. "VAWT Phase 1 Design Review Summary," Stress Engineering Services, SES Doc. No. 1102668-EN-MO-0001 (Rev. B), May 4, 2016.

10. "MC-TLP Concept WAMIT Analysis Output Files," Stress Engineering Services, SES Doc. No. 1102668-EN-MO-0002 (Rev. B), August 8, 2016.

11. "Phase 2 Cost Estimate for Floating VAWT Hull and Moorings," Stress Engineering Services, SES Doc. No. 1102668-EN-PT-0002 (Rev. B), March 28, 2017.

12. "Cost Estimate Classification System," AACE International, Recommended Practice No. 17R-97, November 29, 2011.

Appendix A: Four-column Semi-Submersible Design Details

A.1 Design Iteration #1

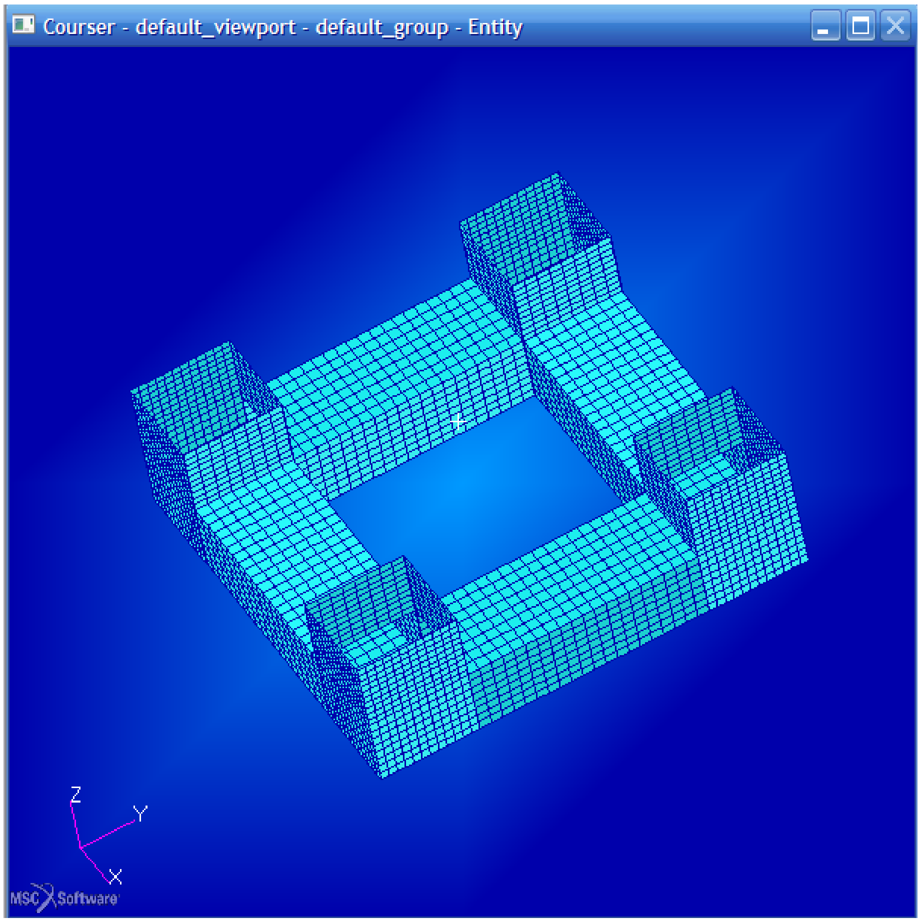
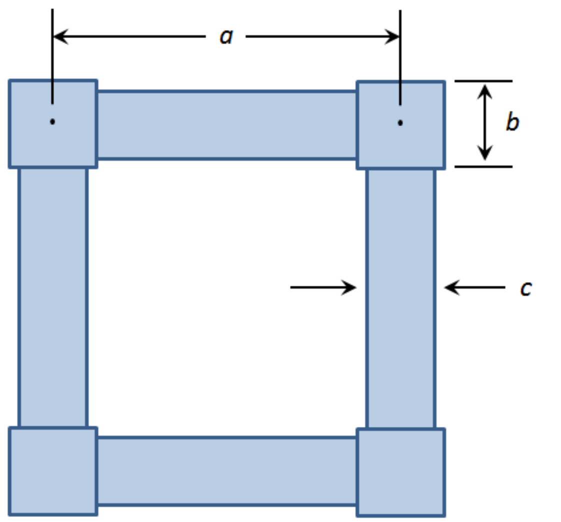
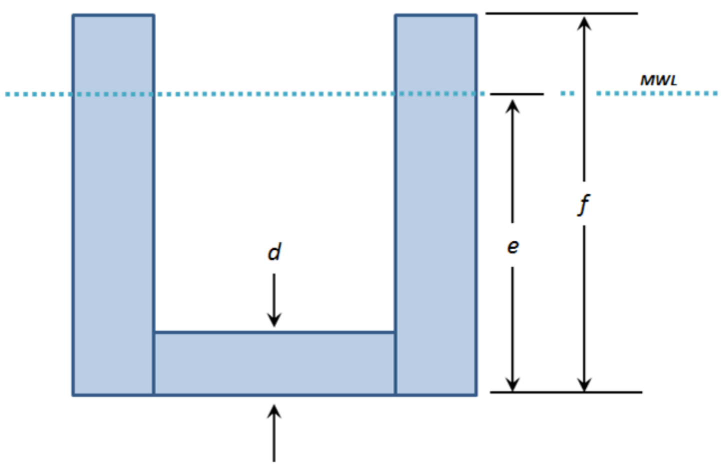


Figure A.1: Patran Model of Vessel



Plan View



Elevation View

Figure A.2: Schematic of Vessel General Dimensions

Table A.1: Vessel General Dimensions and Displacement

Parameter			Value			
Pontoon	Side Pontoon width	***c***	**8**	*m*	26	*ft*
	Side Pontoon height	***d***	**5**	*m*	16	*ft*
	Side Pontoon length		**18**	*m*	60	*ft*
	Side Pontoon lateral spread		**26**	*m*	87	*ft*
	End Pontoon width		**8**	*m*	26	*ft*
	End Pontoon height		**5**	*m*	16	*ft*
	End Pontoon length		**18**	*m*	60	*ft*
	End Pontoon lateral spread		**26**	*m*	87	*ft*
	Pontoon center submergence (all)		**8**	*m*	25	*ft*
	Pontoon volume (total)		**2,897**	m^3	102,308	ft^3
Column	Column width	***b***	**8**	*m*	26	*ft*
	Column longitudinal spread	***a***	**26**	*m*	87	*ft*
	Column lateral spread		**26**	*m*	87	*ft*
	Column height (wrt top)	***f***	**15**	*m*	49	*ft*
	Water plane area		254	m^2	2,729	ft^2
	Immersed column volume		**2,550**	m^3	90,066	ft^3
Vessel Width at Keel			**34**	*m*	113	*ft*
Total Displaced Volume			**5,448**	m^3	192,374	ft^3

Draft	***e***	**10**	*m*	33	*ft*
Displacement		54,766	*kN*	**12,312**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**3.7**	*m*	12	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**8.3**	*m*	27	*ft*
Distance from Keel to Metacenter	***KM***	**12**	*m*	39	*ft*

Table A.2: Vessel Weight and Force Breakdown Groups

Parameter	Value			
Pontoon Steel	6,826	*kN*	**1,535**	*kips*
Special Steel	**683**	*kN*	153	*kips*
Pontoon Outfit and Equipment	**1,024**	*kN*	230	*kips*
Pontoon Subtotal	**8,533**	*kN*	1,918	*kips*
Column Steel	8,996	*kN*	**2,022**	*kips*
Special Steel	**900**	*kN*	202	*kips*
Column Outfit and Equipment	**1,349**	*kN*	303	*kips*
Column Subtotal	**11,245**	*kN*	2,528	*kips*
Deck Steel (basic structure)	**5,580**	*kN*	1,254	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add'l Deck Equipment & Outfit - Marine & Support	**0**	*kN*	0	*kips*
Add'l Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**11,160**	*kN*	2,509	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**558**	*kN*	125	*kips*
Pontoon Fixed Ballast	**0**	*kN*	0	*kips*
LIGHTSHIP	**31,496**	*kN*	7,081	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)	**23,000**	*kN*	5,171	*kips*
Subtotal External Load, Variable Load, and Ballast	**23,270**	*kN*	5,231	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**54,766**	*kN*	12,312	*kips*

Distance from Keel to Center of Gravity	***KG***	**8.0**	*m*	26	*ft*
Distance from Center of Gravity to Metacenter	***GM***	**4.0**	*m*	13	*ft*

Table A.3: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component CG and Mass				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2
Pontoon	Side 1 (East)	7.86	18.43	5.00	724	13.19	0.00	-7.56	217,455	1.90E+07	5.19E+07	4.51E+07	0.00E+00	0.00E+00	2.17E+07
	Side 2 (North)	18.43	7.86	5.00	724	0.00	13.19	-7.56	217,455	5.19E+07	1.90E+07	4.51E+07	0.00E+00	2.17E+07	0.00E+00
	Side 3 (West)	7.86	18.43	5.00	724	-13.19	0.00	-7.56	217,455	1.90E+07	5.19E+07	4.51E+07	0.00E+00	0.00E+00	-2.17E+07
	Side 4 (South)	18.43	7.86	5.00	724	0.00	-13.19	-7.56	217,455	5.19E+07	1.90E+07	4.51E+07	0.00E+00	-2.17E+07	0.00E+00
	Subtotal					0.00	0.00	-7.56	869,819	1.42E+08	1.42E+08	1.81E+08	0.00E+00	0.00E+00	0.00E+00
Column	Column 1 (NE)	7.96	7.96	15.06	955	13.19	13.19	-2.53	286,582	5.87E+07	5.87E+07	1.03E+08	-4.99E+07	9.57E+06	9.57E+06
	Column 2 (NW)	7.96	7.96	15.06	955	-13.19	13.19	-2.53	286,582	5.87E+07	5.87E+07	1.03E+08	4.99E+07	9.57E+06	-9.57E+06
	Column 3 (SW)	7.96	7.96	15.06	955	-13.19	-13.19	-2.53	286,582	5.87E+07	5.87E+07	1.03E+08	-4.99E+07	-9.57E+06	-9.57E+06
	Column 4 (SE)	7.96	7.96	15.06	955	13.19	-13.19	-2.53	286,582	5.87E+07	5.87E+07	1.03E+08	4.99E+07	-9.57E+06	9.57E+06
	Subtotal					0.00	0.00	-2.53	1,146,329	2.35E+08	2.35E+08	4.11E+08	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	5.00	568,800	3.39E+07	3.39E+07	3.79E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	27.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	27.50	298,000	1.24E+09	1.27E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	27.50	50,000						
	Subtotal					0.00	0.00	16.25	1,137,600	1.27E+09	1.31E+09	7.27E+07	0.00E+00	0.00E+00	0.00E+00
Pontoon Fixed Ballast	Side 1 (East)	7.86	18.43	0.00	0	13.19	0.00	-10.06	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Side 2 (North)	18.43	7.86	0.00	0	0.00	13.19	-10.06	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Side 3 (West)	7.86	18.43	0.00	0	-13.19	0.00	-10.06	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Side 4 (South)	18.43	7.86	0.00	0	0.00	-13.19	-10.06	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Subtotal					0.00	0.00	0.00	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Ballast	Side 1 (East)	7.86	18.43	2.75	398	13.19	0.00	-8.69	407,806	4.26E+07	1.04E+08	8.46E+07	0.00E+00	0.00E+00	4.67E+07
	Side 2 (North)	18.43	7.86	2.75	398	0.00	13.19	-8.69	407,806	1.04E+08	4.26E+07	8.46E+07	0.00E+00	4.67E+07	0.00E+00
	Side 3 (West)	7.86	18.43	2.75	398	-13.19	0.00	-8.69	407,806	4.26E+07	1.04E+08	8.46E+07	0.00E+00	0.00E+00	-4.67E+07
	Side 4 (South)	18.43	7.86	2.75	398	0.00	-13.19	-8.69	407,806	1.04E+08	4.26E+07	8.46E+07	0.00E+00	-4.67E+07	0.00E+00
	Column 1 (NE)	7.96	7.96	2.74	174	13.19	13.19	-8.69	178,331	4.56E+07	4.56E+07	6.40E+07	-3.10E+07	2.04E+07	2.04E+07
	Column 2 (NW)	7.96	7.96	2.74	174	-13.19	13.19	-8.69	178,331	4.56E+07	4.56E+07	6.40E+07	3.10E+07	2.04E+07	-2.04E+07
	Column 3 (SW)	7.96	7.96	2.74	174	-13.19	-13.19	-8.69	178,331	4.56E+07	4.56E+07	6.40E+07	-3.10E+07	-2.04E+07	-2.04E+07
	Column 4 (SE)	7.96	7.96	2.74	174	13.19	-13.19	-8.69	178,331	4.56E+07	4.56E+07	6.40E+07	3.10E+07	-2.04E+07	2.04E+07
	Subtotal				2,287	0.00	0.00	-8.69	2,344,546	4.76E+08	4.76E+08	5.94E+08	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	5.00	56,880	3.39E+06	3.39E+06	3.79E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Sub Total					0.00	0.00	5.00	56,880	3.39E+06	3.39E+06	3.79E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						**0.00**	**0.00**	**-1.99**	**5,555,174**	**2.13E+09**	**2.16E+09**	**1.26E+09**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table A.4: Principal Mooring Details

Mooring Line #	Fairlead Location X m	Fairlead Location Y m	Fairlead Location Z m	Pile Location X m	Pile Location Y m	Pile Location Z m	Line Length m	Line Diameter mm	MBL kN	EA kN
1	17.0	-13.0	-13.0	400.0	0.0	-150.0	406.8	60	1000	15,000
2	17.0	13.0	-13.0	400.0	0.0	-150.0	406.8	60	1000	15,000
3	13.0	17.0	-13.0	0.0	400.0	-150.0	406.8	60	1000	15,000
4	-13.0	17.0	-13.0	0.0	400.0	-150.0	406.8	60	1000	15,000
5	-17.0	13.0	-13.0	-400.0	0.0	-150.0	406.8	60	1000	15,000
6	-17.0	-13.0	-13.0	-400.0	0.0	-150.0	406.8	60	1000	15,000
7	-13.0	-17.0	-13.0	0.0	-400.0	-150.0	406.8	60	1000	15,000
8	13.0	-17.0	-13.0	0.0	-400.0	-150.0	406.8	60	1000	15,000

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness (15×MBL)

Table A.5: Principal Vessel and Mooring Stiffness Values

Vessel Hydrostatic Stiffness			Mooring System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	1.33E+05	*N/m*	K_{11}	1.33E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	1.33E+05	*N/m*	K_{22}	1.33E+05	*N/m*
K_{33}	2.55E+06	*N/m*	K_{33}	3.51E+04	*N/m*	K_{33}	2.59E+06	*N/m*
K_{44}	3.78E+06	*(N-m)/deg*	K_{44}	3.53E+05	*(N-m)/deg*	K_{44}	4.13E+06	*(N-m)/deg*
K_{55}	3.78E+06	*(N-m)/deg*	K_{55}	3.53E+05	*(N-m)/deg*	K_{55}	4.13E+06	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	1.08E+06	*(N-m)/deg*	K_{66}	1.08E+06	*(N-m)/deg*

Table A.6: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	5.56E+06	*kg*	M_{11}	3.63E+06	*kg*	M_{11}	9.19E+06	*kg*
M_{22}	5.56E+06	*kg*	M_{22}	3.63E+06	*kg*	M_{22}	9.19E+06	*kg*
M_{33}	5.56E+06	*kg*	M_{33}	7.75E+06	*kg*	M_{33}	1.33E+07	*kg*
I_{44}	2.13E+09	*kg-m²*	I_{44}	8.18E+08	*kg-m²*	I_{44}	2.95E+09	*kg-m²*
I_{55}	2.16E+09	*kg-m²*	I_{55}	8.18E+08	*kg-m²*	I_{55}	2.98E+09	*kg-m²*
I_{66}	1.26E+09	*kg-m²*	I_{66}	6.84E+08	*kg-m²*	I_{66}	1.95E+09	*kg-m²*

Table A.7: System Natural Periods

System Natural Periods		
Surge	52.3	*sec*
Sway	52.3	*sec*
Heave	14.3	*sec*
Pitch	22.2	*sec*
Roll	22.3	*sec*
Yaw	35.3	*sec*

Table A.8: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	19.2	*deg*
Pitch	19.2	*deg*
Yaw	6.8	*deg*

A.2 Design Iteration #2

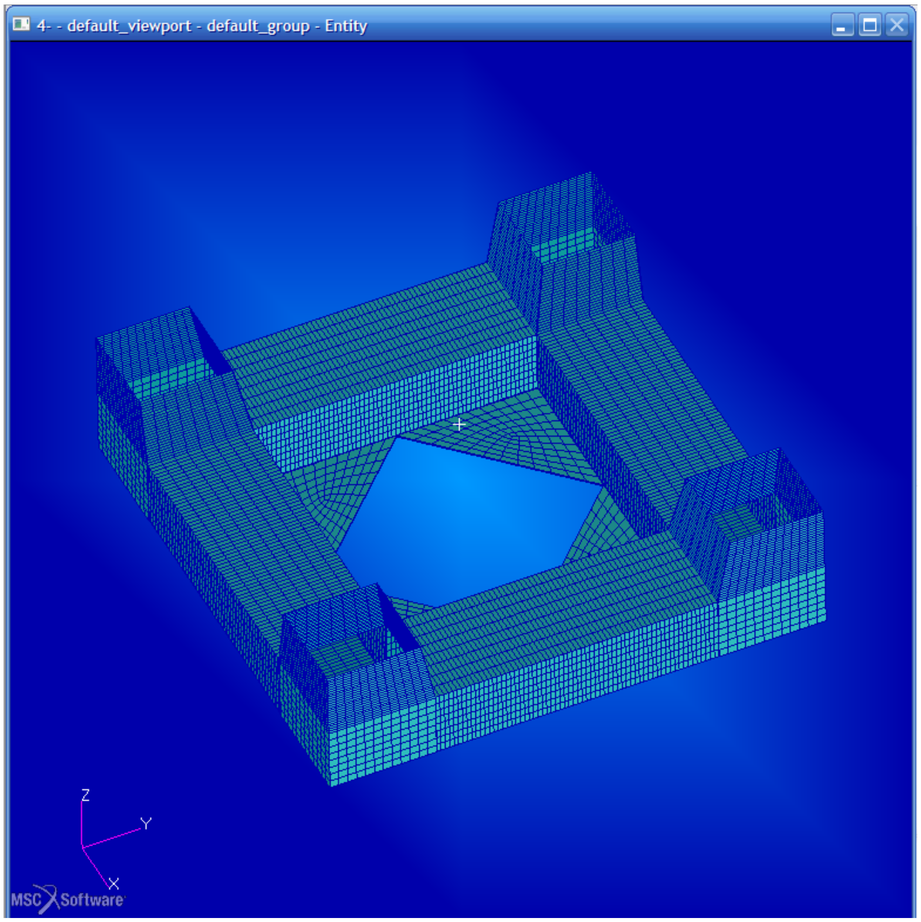


Figure A.3: Patran Model of Vessel

Table A.9: Vessel General Dimensions and Displacement

Parameter			Value			
Pontoon	Side Pontoon width	***c***	**8**	*m*	26	*ft*
	Side Pontoon height	***d***	**5**	*m*	16	*ft*
	Side Pontoon length		**21**	*m*	69	*ft*
	Side Pontoon lateral spread		**29**	*m*	95	*ft*
	End Pontoon width		**8**	*m*	26	*ft*
	End Pontoon height		**5**	*m*	16	*ft*
	End Pontoon length		**21**	*m*	69	*ft*
	End Pontoon lateral spread		**29**	*m*	95	*ft*
	Pontoon center submergence (all)		**8**	*m*	25	*ft*
	Pontoon volume (total)		**3,308**	m^3	116,811	ft^3
Column	Column width (at base)	***b***	**8**	*m*	26	*ft*
	Column cross-section (at base)		**63**	m^2	682	ft^2
	Column submerged depth (draft)	***e***	**10**	*m*	33	*ft*
	Column longitudinal spread	***a***	**29**	*m*	95	*ft*
	Column lateral spread		**29**	*m*	95	*ft*
	Column height (wrt top)	***f***	**15**	*m*	49	*ft*
	Water plane area		254	m^2	2,729	ft^2
	Immersed column volume		**2,550**	m^3	90,066	ft^3
Vessel Width at Keel			**37**	*m*	121	*ft*
Total Displaced Volume			**5,858**	m^3	206,877	ft^3

Draft	***e***	**10**	*m*	33	*ft*
Displacement		58,895	*kN*	**13,240**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**3.6**	*m*	12	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**7.6**	*m*	25	*ft*
Distance from Keel to Metacenter	***KM***	**11**	*m*	37	*ft*

Table A.10: Vessel Weight and Force Breakdown Groups

Parameter	Value			
Pontoon Steel	7,794	*kN*	**1,752**	*kips*
Special Steel	**779**	*kN*	175	*kips*
Pontoon Outfit and Equipment	**1,169**	*kN*	263	*kips*
Pontoon Subtotal	**9,742**	*kN*	2,190	*kips*
Column Steel	8,996	*kN*	**2,022**	*kips*
Special Steel	**900**	*kN*	202	*kips*
Column Outfit and Equipment	**1,349**	*kN*	303	*kips*
Column Subtotal	**11,245**	*kN*	2,528	*kips*
Deck Steel (basic structure)	**5,580**	*kN*	1,254	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add'l Deck Equipment & Outfit - Marine & Support	**0**	*kN*	0	*kips*
Add'l Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**11,160**	*kN*	2,509	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**558**	*kN*	125	*kips*
Pontoon Fixed Ballast	**0**	*kN*	0	*kips*
LIGHTSHIP	**32,706**	*kN*	7,353	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)	**25,919**	*kN*	5,827	*kips*
Subtotal External Load, Variable Load, and Ballast	**26,189**	*kN*	5,888	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**58,895**	*kN*	13,240	*kips*

Distance from Keel to Center of Gravity	***KG***	**7.6**	*m*	25	*ft*
Distance from Center of Gravity to Metacenter	***GM***	**3.6**	*m*	12	*ft*

Table A.11: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component CG and Mass				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2
Pontoon	Side 1 (East)	7.86	21.04	5.00	827	14.50	0.00	-7.56	248,280	2.39E+07	6.82E+07	6.26E+07	0.00E+00	0.00E+00	2.72E+07
	Side 2 (North)	21.04	7.86	5.00	827	0.00	14.50	-7.56	248,280	6.82E+07	2.39E+07	6.26E+07	0.00E+00	2.72E+07	0.00E+00
	Side 3 (West)	7.86	21.04	5.00	827	-14.50	0.00	-7.56	248,280	2.39E+07	6.82E+07	6.26E+07	0.00E+00	0.00E+00	-2.72E+07
	Side 4 (South)	21.04	7.86	5.00	827	0.00	-14.50	-7.56	248,280	6.82E+07	2.39E+07	6.26E+07	0.00E+00	-2.72E+07	0.00E+00
	Subtotal					0.00	0.00	-7.56	993,119	1.84E+08	1.84E+08	2.51E+08	0.00E+00	0.00E+00	0.00E+00
Column	Column 1 (NE)	7.96	7.96	15.06	955	14.50	14.50	-2.53	286,582	6.90E+07	6.90E+07	1.24E+08	-6.03E+07	1.05E+07	1.05E+07
	Column 2 (NW)	7.96	7.96	15.06	955	-14.50	14.50	-2.53	286,582	6.90E+07	6.90E+07	1.24E+08	6.03E+07	1.05E+07	-1.05E+07
	Column 3 (SW)	7.96	7.96	15.06	955	-14.50	-14.50	-2.53	286,582	6.90E+07	6.90E+07	1.24E+08	-6.03E+07	-1.05E+07	-1.05E+07
	Column 4 (SE)	7.96	7.96	15.06	955	14.50	-14.50	-2.53	286,582	6.90E+07	6.90E+07	1.24E+08	6.03E+07	-1.05E+07	1.05E+07
	Subtotal					0.00	0.00	-2.53	1,146,329	2.76E+08	2.76E+08	4.94E+08	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	5.00	568,800	3.39E+07	3.39E+07	3.79E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	27.50	220,800	1.24E+09	1.27E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Drivetrain	--	--	--	--	0.00	0.00	27.50	298,000						
	Additional Deck Equipment	--	--	--	--	0.00	0.00	27.50	50,000						
	Subtotal					0.00	0.00	16.25	1,137,600	1.27E+09	1.31E+09	7.27E+07	0.00E+00	0.00E+00	0.00E+00
Pontoon Fixed Ballast	Side 1 (East)	7.86	21.04	0.00	0	14.50	0.00	-10.06	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Side 2 (North)	21.04	7.86	0.00	0	0.00	14.50	-10.06	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Side 3 (West)	7.86	21.04	0.00	0	-14.50	0.00	-10.06	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Side 4 (South)	21.04	7.86	0.00	0	0.00	-14.50	-10.06	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Subtotal					0.00	0.00	0.00	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Ballast	Side 1 (East)	7.86	21.04	2.82	466	14.50	0.00	-8.65	477,610	5.37E+07	1.39E+08	1.20E+08	0.00E+00	0.00E+00	5.99E+07
	Side 2 (North)	21.04	7.86	2.82	466	0.00	14.50	-8.65	477,610	1.39E+08	5.37E+07	1.20E+08	0.00E+00	5.99E+07	0.00E+00
	Side 3 (West)	7.86	21.04	2.82	466	-14.50	0.00	-8.65	477,610	5.37E+07	1.39E+08	1.20E+08	0.00E+00	0.00E+00	-5.99E+07
	Side 4 (South)	21.04	7.86	2.82	466	0.00	-14.50	-8.65	477,610	1.39E+08	5.37E+07	1.20E+08	0.00E+00	-5.99E+07	0.00E+00
	Column 1 (NE)	7.96	7.96	2.82	178	14.50	14.50	-8.65	182,915	5.32E+07	5.32E+07	7.88E+07	-3.85E+07	2.29E+07	2.29E+07
	Column 2 (NW)	7.96	7.96	2.82	178	-14.50	14.50	-8.65	182,915	5.32E+07	5.32E+07	7.88E+07	3.85E+07	2.29E+07	-2.29E+07
	Column 3 (SW)	7.96	7.96	2.82	178	-14.50	-14.50	-8.65	182,915	5.32E+07	5.32E+07	7.88E+07	-3.85E+07	-2.29E+07	-2.29E+07
	Column 4 (SE)	7.96	7.96	2.82	178	14.50	-14.50	-8.65	182,915	5.32E+07	5.32E+07	7.88E+07	3.85E+07	-2.29E+07	2.29E+07
	Subtotal				2,577	0.00	0.00	-8.65	2,642,100	5.98E+08	5.98E+08	7.97E+08	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	5.00	56,880	3.39E+06	3.39E+06	3.79E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	5.00	56,880	3.39E+06	3.39E+06	3.79E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						**0.00**	**0.00**	**-2.43**	**5,976,028**	**2.33E+09**	**2.37E+09**	**1.62E+09**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table A.12: Principal Mooring Details

Mooring Line	Fairlead Location			Pile Location			Line Length	Line Diameter	MBL	EA
	X	Y	Z	X	Y	Z				
#	m	m	m	m	m	m	m	mm	kN	kN
1	20.0	-13.0	-13.0	400.0	0.0	-150.0	403.9	60	1000	15,000
2	20.0	13.0	-13.0	400.0	0.0	-150.0	403.9	60	1000	15,000
3	13.0	20.0	-13.0	0.0	400.0	-150.0	403.9	60	1000	15,000
4	-13.0	20.0	-13.0	0.0	400.0	-150.0	403.9	60	1000	15,000
5	-20.0	13.0	-13.0	-400.0	0.0	-150.0	403.9	60	1000	15,000
6	-20.0	-13.0	-13.0	-400.0	0.0	-150.0	403.9	60	1000	15,000
7	-13.0	-20.0	-13.0	0.0	-400.0	-150.0	403.9	60	1000	15,000
8	13.0	-20.0	-13.0	0.0	-400.0	-150.0	403.9	60	1000	15,000

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness (15×MBL)

Table A.13: Principal Vessel and Mooring Stiffness Values

Vessel Hydrostatic Stiffness			Mooring System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	1.34E+05	*N/m*	K_{11}	1.34E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	1.34E+05	*N/m*	K_{22}	1.34E+05	*N/m*
K_{33}	1.95E+06	*N/m*	K_{33}	3.58E+04	*N/m*	K_{33}	1.99E+06	*N/m*
K_{44}	3.64E+06	*(N-m)/deg*	K_{44}	3.43E+05	*(N-m)/deg*	K_{44}	3.98E+06	*(N-m)/deg*
K_{55}	3.64E+06	*(N-m)/deg*	K_{55}	3.43E+05	*(N-m)/deg*	K_{55}	3.98E+06	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	1.13E+06	*(N-m)/deg*	K_{66}	1.13E+06	*(N-m)/deg*

Table A.14: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	5.98E+06	*kg*	M_{11}	3.83E+06	*kg*	M_{11}	9.81E+06	*kg*
M_{22}	5.98E+06	*kg*	M_{22}	3.81E+06	*kg*	M_{22}	9.78E+06	*kg*
M_{33}	5.98E+06	*kg*	M_{33}	1.29E+07	*kg*	M_{33}	1.89E+07	*kg*
I_{44}	2.33E+09	*kg-m*^{2}	I_{44}	1.30E+09	*kg-m*^{2}	I_{44}	3.64E+09	*kg-m*^{2}
I_{55}	2.37E+09	*kg-m*^{2}	I_{55}	1.28E+09	*kg-m*^{2}	I_{55}	3.65E+09	*kg-m*^{2}
I_{66}	1.62E+09	*kg-m*^{2}	I_{66}	8.18E+08	*kg-m*^{2}	I_{66}	2.44E+09	*kg-m*^{2}

Table A.15: System Natural Periods

System Natural Periods		
Surge	53.8	*sec*
Sway	53.8	*sec*
Heave	19.4	*sec*
Roll	25.1	*sec*
Pitch	25.1	*sec*
Yaw	38.5	*sec*

Table A.16: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	19.9	*deg*
Pitch	19.9	*deg*
Yaw	6.4	*deg*

Appendix B: Classic Spar Design Details

B.1 Design Iteration #1

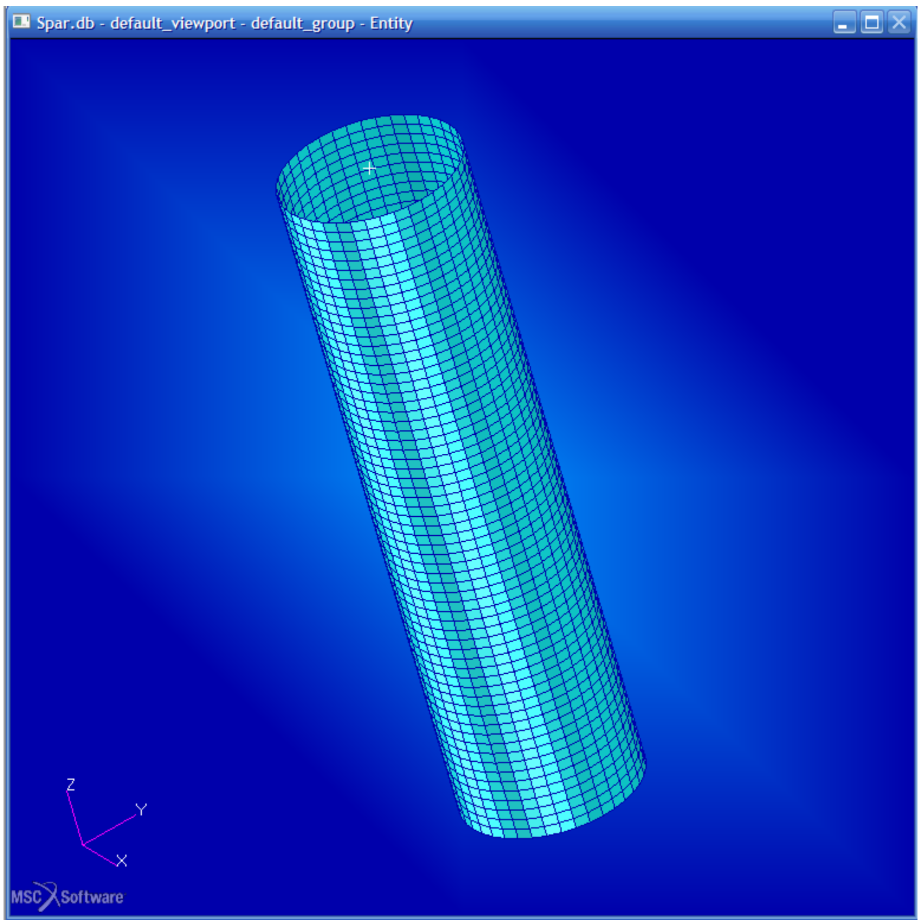
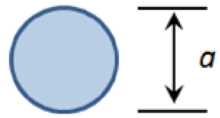
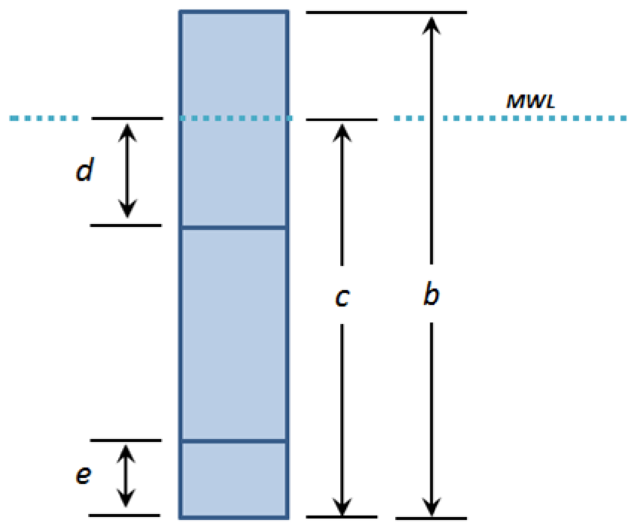


Figure B.1: Patran Model of Vessel



Plan View



Elevation View

Figure B.2: Schematic of Vessel General Dimensions

Table B.1: Vessel General Dimensions and Displacement

Parameter			Value			
Spar Column	Spar diameter	***a***	**17**	*m*	56	*ft*
	Spar height (wrt top)	***b***	**75**	*m*	245	*ft*
	Hard tank draft	***d***	**20**	*m*	66	*ft*
	Height of soft tank	***e***	**3**	*m*	10	*ft*
	Water plane area		**232**	m^2	2,502	ft^2
Displaced Volumes	Hard tank (void)		**3,694**	m^3	130,455	ft^3
	Hard tank (variable)		**971**	m^3	34,300	ft^3
	Mid-section		**10,850**	m^3	383,162	ft^3
	Soft tank		**697**	m^3	24,628	ft^3
	Fixed ballast		**--**	m^3	--	ft^3
	Total displaced volume		**16,213**	m^3	572,545	ft^3

Draft	***c***	**70**	*m*	229	*ft*
Displacement		162,996	*kN*	**36,643**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**35**	*m*	114	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**0.265**	*m*	1	*ft*
Distance from Keel to Metacenter	***KM***	**35**	*m*	115	*ft*

Table B.2: Vessel Weight and Force Breakdown Groups

Parameter	Value			
Hard Tank Steel	**7,311**	*kN*	1,644	*kips*
Mid-section Steel	**9,899**	*kN*	2,225	*kips*
Soft Tank Steel	**1,273**	*kN*	286	*kips*
Spar Hull Steel Subtotal	**18,482**	*kN*	4,155	*kips*
Special Steel	**1,848**	*kN*	416	*kips*
Spar Hull Outfit and Equipment	**2,772**	*kN*	623	*kips*
Spar Hull Subtotal	**23,103**	*kN*	5,194	*kips*
Deck Steel (basic structure)	7,842	*kN*	**1,763**	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Addl. Deck Equipment & Outfit - Marine & Support	**0**	*kN*	0	*kips*
Addl. Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**13,422**	*kN*	3,017	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**784**	*kN*	176	*kips*
Hull Fixed Ballast	**10,738**	*kN*	2,414	*kips*
LIGHTSHIP	**48,047**	*kN*	10,801	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (hard tank)	**2,000**	*kN*	450	*kips*
Entrained Water (mid-section)	**109,103**	*kN*	24,527	*kips*
Entrained Water (soft tank)	**3,576**	*kN*	804	*kips*
Subtotal External Load, Variable Load, Ballast, Entrained Water	**114,949**	*kN*	25,841	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**162,996**	*kN*	36,643	*kips*

Distance from Keel to Center of Gravity	***KG***	**31.1**	*m*	102	*ft*
Distance from Center of Gravity to Metacenter	***GM***	**4.0**	*m*	13	*ft*

Table B.3: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component CG and Mass				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2
Spar Hull	Hard Tank (Void)	--	--	20.89	4,857	0.00	0.00	-5.45	776,292	6.56E+07	6.56E+07	2.87E+07	0.00E+00	0.00E+00	0.00E+00
	Hard Tank (Variable)	--	--	4.18	971	0.00	0.00	-17.98	155,258	5.33E+07	5.33E+07	5.74E+06	0.00E+00	0.00E+00	0.00E+00
	Mid-section Steel	--	--	46.67		0.00	0.00	-43.41	1,261,352	2.63E+09	2.63E+09	4.67E+07	0.00E+00	0.00E+00	0.00E+00
	Soft Tank	--	--	3.00	697	0.00	0.00	-68.24	162,147	7.58E+08	7.58E+08	6.00E+06	0.00E+00	0.00E+00	0.00E+00
	Subtotal					0.00	0.00	-30.93	2,355,048	3.51E+09	3.51E+09	8.71E+07	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	5.00	799,410	4.77E+07	4.77E+07	5.33E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	27.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	27.50	298,000	1.24E+09	1.27E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	27.50	50,000						
	Subtotal					0.00	0.00	14.35	1,368,210	1.29E+09	1.32E+09	8.81E+07	0.00E+00	0.00E+00	0.00E+00
Ballast	Fixed Ballast	--	--	1.47	--	0.00	0.00	-69.01	1,094,568	5.23E+09	5.23E+09	4.05E+07	0.00E+00	0.00E+00	0.00E+00
	Variable Ballast	--	--	4.18	--	0.00	0.00	-19.64	203,874	8.27E+07	8.27E+07	7.54E+06	0.00E+00	0.00E+00	0.00E+00
	Subtotal					0.00	0.00	-61.26	1,298,442	5.32E+09	5.32E+09	4.80E+07	0.00E+00	0.00E+00	0.00E+00
Entrained Water	Mid-section	--	--	46.67		0.00	0.00	-43.41	11,121,586	2.32E+10	2.32E+10	4.11E+08	0.00E+00	0.00E+00	0.00E+00
	Soft Tank	--	--	3.00		0.00	0.00	-67.51	364,511	1.67E+09	1.67E+09	1.35E+07	0.00E+00	0.00E+00	0.00E+00
	Subtotal					0.00	0.00	-44.17	11,486,098	2.48E+10	2.48E+10	4.25E+08	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	5.00	79,941	4.77E+06	4.77E+06	5.33E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	5.00	79,941	4.77E+06	4.77E+06	5.33E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						**0.00**	**0.00**	**-38.56**	**16,587,739**	**3.50E+10**	**3.50E+10**	**6.54E+08**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table B.4: Principal Mooring Details

Mooring Line #	Fairlead Location X m	Fairlead Location Y m	Fairlead Location Z m	Pile Location X m	Pile Location Y m	Pile Location Z m	Line Length m	Line Diameter mm	MBL kN	EA kN
1	11.5	-11.5	-23.0	400.0	0.0	-150.0	408.7	60.0	1000	15,000
2	11.5	11.5	-23.0	400.0	0.0	-150.0	408.7	60.0	1000	15,000
3	11.5	11.5	-23.0	0.0	400.0	-150.0	408.7	60.0	1000	15,000
4	-11.5	11.5	-23.0	0.0	400.0	-150.0	408.7	60.0	1000	15,000
5	-11.5	11.5	-23.0	-400.0	0.0	-150.0	408.7	60.0	1000	15,000
6	-11.5	-11.5	-23.0	-400.0	0.0	-150.0	408.7	60.0	1000	15,000
7	-11.5	-11.5	-23.0	0.0	-400.0	-150.0	408.7	60.0	1000	15,000
8	11.5	-11.5	-23.0	0.0	-400.0	-150.0	408.7	60.0	1000	15,000

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness (15×MBL)

Table B.5: Principal Vessel and Mooring Stiffness Values

Vessel Hydrostatic Stiffness			Mooring System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	1.35E+05	*N/m*	K_{11}	1.35E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	1.35E+05	*N/m*	K_{22}	1.35E+05	*N/m*
K_{33}	2.33E+06	*N/m*	K_{33}	3.05E+04	*N/m*	K_{33}	2.36E+06	*N/m*
K_{44}	1.14E+07	*(N-m)/deg*	K_{44}	1.12E+06	*(N-m)/deg*	K_{44}	1.25E+07	*(N-m)/deg*
K_{55}	1.14E+07	*(N-m)/deg*	K_{55}	1.12E+06	*(N-m)/deg*	K_{55}	1.25E+07	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	8.19E+05	*(N-m)/deg*	K_{66}	8.19E+05	*(N-m)/deg*

Table B.6: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	1.66E+07	*kg*	M_{11}	1.53E+07	*kg*	M_{11}	3.19E+07	*kg*
M_{22}	1.66E+07	*kg*	M_{22}	1.53E+07	*kg*	M_{22}	3.19E+07	*kg*
M_{33}	1.66E+07	*kg*	M_{33}	1.35E+06	*kg*	M_{33}	1.79E+07	*kg*
I_{44}	3.50E+10	*kg-m*^{2}	I_{44}	2.18E+10	*kg-m*^{2}	I_{44}	5.68E+10	*kg-m*^{2}
I_{55}	3.50E+10	*kg-m*^{2}	I_{55}	2.18E+10	*kg-m*^{2}	I_{55}	5.68E+10	*kg-m*^{2}
I_{66}	6.54E+08	*kg-m*^{2}	I_{66}	1.90E-03	*kg-m*^{2}	I_{66}	6.54E+08	*kg-m*^{2}

Table B.7: System Natural Periods

System Natural Periods		
Surge	96.7	*sec*
Sway	96.7	*sec*
Heave	17.3	*sec*
Roll	56.0	*sec*
Pitch	56.0	*sec*
Yaw	23.5	*sec*

Table B.8: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	6.4	*deg*
Pitch	6.4	*deg*
Yaw	8.9	*deg*

B.2 Design Iteration #2

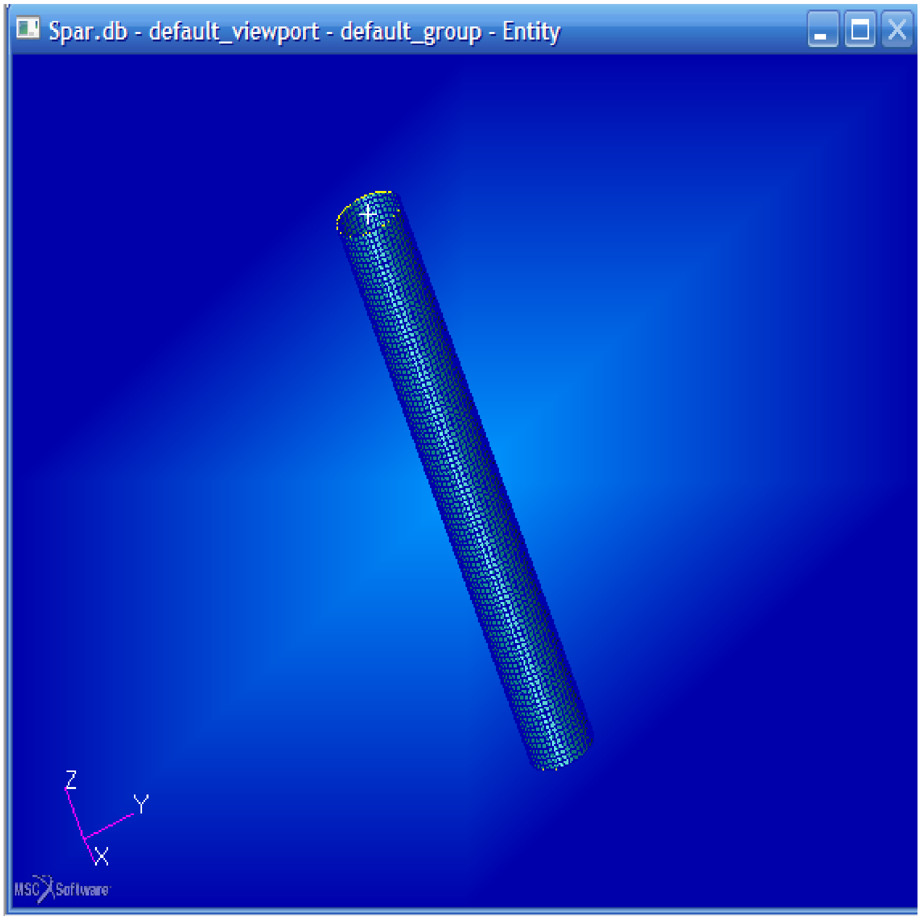


Figure B.4: Patran Model of Vessel

Table B.9: Vessel General Dimensions and Displacement

Vessel General Dimensions and Displacement						
Spar Column	Spar diameter	***a***	**12**	*m*	39	*ft*
	Spar height (wt top)	***b***	**105**	*m*	344	*ft*
	Hard tank draft	***d***	**40**	*m*	131	*ft*
	Height of soft tank	***e***	**4**	*m*	13	*ft*
	Water plane area		**113**	m^2	1,217	ft^2
Displaced Volumes	Hard tank (void)		**3,676**	m^3	129,800	ft^3
	Hard tank (variable)		**848**	m^3	29,954	ft^3
	Mid-section		**6,333**	m^3	223,656	ft^3
	Soft tank		**452**	m^3	15,975	ft^3
	Total displaced volume		**11,310**	m^3	399,385	ft^3

Draft	***c***	**100**	*m*	328	*ft*
Displacement		113,699	*kN*	**25,561**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**50**	*m*	164	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**0.090**	*m*	0	*ft*
Distance from Keel to Metacenter	***KM***	**50**	*m*	164	*ft*

Table B.10: Vessel Weight and Force Breakdown Groups

Vessel Weight and Force Breakdown Groups				
Hard Tank Steel	**10,817**	*kN*	2,432	*kips*
Mid-section Steel	**9,837**	*kN*	2,212	*kips*
Soft Tank Steel	**1,405**	*kN*	316	*kips*
Spar Hull Steel Subtotal	**22,060**	*kN*	4,959	*kips*
Special Steel	**2,206**	*kN*	496	*kips*
Spar Hull Outfit and Equipment	**3,309**	*kN*	744	*kips*
Spar Hull Subtotal	**27,575**	*kN*	6,199	*kips*
Deck Steel (basic structure)	1,632	*kN*	**367**	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add'l Deck Equipment & Outfit - Marine & Support	**0**	*kN*	0	*kips*
Add'l Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**7,212**	*kN*	1,621	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**163**	*kN*	37	*kips*
Hull Fixed Ballast	**5,770**	*kN*	1,297	*kips*
LIGHTSHIP	**40,721**	*kN*	9,154	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (hard tank)	**6,322**	*kN*	1,421	*kips*
Entrained Water (mid-section)	**63,684**	*kN*	14,317	*kips*
Entrained Water (soft tank)	**2,702**	*kN*	607	*kips*
Subtotal External Load, Variable Load, Ballast, Entrained Water	**72,979**	*kN*	16,406	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**113,700**	*kN*	25,561	*kips*

Distance from Keel to Center of Gravity	***KG***	**43**	*m*	140	*ft*
Distance from Center of Gravity to Metacenter	***GM***	**7.3**	*m*	24	*ft*

Table B.11: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component CG and Mass				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	$kg\text{-}m^2$	$kg\text{-}m^2$	$kg\text{-}m^2$	$kg\text{-}m^2$	$kg\text{-}m^2$	$kg\text{-}m^2$
Spar Hull	Hard Tank (Void)	--	--	37.50	4,241	0.00	0.00	-13.75	1,148,645	3.62E+08	3.62E+08	2.07E+07	0.00E+00	0.00E+00	0.00E+00
	Hard Tank (Variable)	--	--	7.50	848	0.00	0.00	-36.25	229,729	3.05E+08	3.05E+08	4.14E+06	0.00E+00	0.00E+00	0.00E+00
	Mid-section Steel	--	--	56.00		0.00	0.00	-68.00	1,253,495	6.14E+09	6.14E+09	2.26E+07	0.00E+00	0.00E+00	0.00E+00
	Soft Tank	--	--	4.00	452	0.00	0.00	-98.00	179,071	1.72E+09	1.72E+09	3.22E+06	0.00E+00	0.00E+00	0.00E+00
	Subtotal					0.00	0.00	-45.15	2,810,940	8.52E+09	8.52E+09	5.06E+07	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	5.00	166,412	9.93E+06	9.93E+06	1.11E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	27.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	27.50	298,000	1.24E+09	1.27E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	27.50	50,000						
	Subtotal					0.00	0.00	22.41	735,212	1.25E+09	1.28E+09	4.59E+07	0.00E+00	0.00E+00	0.00E+00
Ballast	Fixed Ballast	--	--	1.62	--	0.00	0.00	-99.19	588,169	5.79E+09	5.79E+09	1.06E+07	0.00E+00	0.00E+00	0.00E+00
	Variable Ballast	--	--	7.50	--	0.00	0.00	-37.22	644,444	9.02E+08	9.02E+08	1.16E+07	0.00E+00	0.00E+00	0.00E+00
	Subtotal					0.00	0.00	-66.79	1,232,614	6.69E+09	6.69E+09	2.22E+07	0.00E+00	0.00E+00	0.00E+00
Entrained Water	Mid-section	--	--	56.00		0.00	0.00	-68.00	6,491,787	3.18E+10	3.18E+10	1.17E+08	0.00E+00	0.00E+00	0.00E+00
	Soft Tank	--	--	4.00		0.00	0.00	-97.19	275,449	2.60E+09	2.60E+09	4.96E+06	0.00E+00	0.00E+00	0.00E+00
	Subtotal					0.00	0.00	-69.19	6,767,236	3.44E+10	3.44E+10	1.22E+08	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	5.00	16,641	9.93E+05	9.93E+05	1.11E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	5.00	16,641	9.93E+05	9.93E+05	1.11E+06	0.00E+00	0.00E+00	0.00E+00
Total						**0.00**	**0.00**	**-57.16**	**11,562,643**	**5.08E+10**	**5.09E+10**	**2.42E+08**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table B.12: Principal Mooring Details

Mooring Line #	Fairlead Location X m	Fairlead Location Y m	Fairlead Location Z m	Pile Location X m	Pile Location Y m	Pile Location Z m	Line Length m	Line Diameter mm	MBL kN	EA kN
1	4.25	-4.25	-35.0	400.0	0.0	-150.0	412.1	132	4900	73,500
2	4.25	4.25	-35.0	400.0	0.0	-150.0	412.1	132	4900	73,500
3	4.25	4.25	-35.0	0.0	400.0	-150.0	412.1	132	4900	73,500
4	-4.25	4.25	-35.0	0.0	400.0	-150.0	412.1	132	4900	73,500
5	-4.25	4.25	-35.0	-400.0	0.0	-150.0	412.1	132	4900	73,500
6	-4.25	-4.25	-35.0	-400.0	0.0	-150.0	412.1	132	4900	73,500
7	-4.25	-4.25	-35.0	0.0	-400.0	-150.0	412.1	132	4900	73,500
8	4.25	-4.25	-35.0	0.0	-400.0	-150.0	412.1	132	4900	73,500

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness (15×MBL)

Table B.13: Principal Vessel and Mooring Stiffness Values

Vessel Hydrostatic Stiffness			Mooring System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	6.60E+05	*N/m*	K_{11}	6.60E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	6.60E+05	*N/m*	K_{22}	6.60E+05	*N/m*
K_{33}	8.11E+05	*N/m*	K_{33}	1.14E+05	*N/m*	K_{33}	9.25E+05	*N/m*
K_{44}	4.24E+07	*(N-m)/deg*	K_{44}	1.34E+07	*(N-m)/deg*	K_{44}	5.58E+07	*(N-m)/deg*
K_{55}	4.24E+07	*(N-m)/deg*	K_{55}	1.34E+07	*(N-m)/deg*	K_{55}	5.58E+07	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	4.93E+05	*(N-m)/deg*	K_{66}	4.93E+05	*(N-m)/deg*

Table B.14: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	1.16E+07	*kg*	M_{11}	1.12E+07	*kg*	M_{11}	2.27E+07	*kg*
M_{22}	1.16E+07	*kg*	M_{22}	1.12E+07	*kg*	M_{22}	2.27E+07	*kg*
M_{33}	1.16E+07	*kg*	M_{33}	2.54E+05	*kg*	M_{33}	1.18E+07	*kg*
I_{44}	5.08E+10	*kg-m²*	I_{44}	3.46E+10	$kg\text{-}m^2$	I_{44}	8.55E+10	$kg\text{-}m^2$
I_{55}	5.09E+10	$kg\text{-}m^2$	I_{55}	3.46E+10	$kg\text{-}m^2$	I_{55}	8.55E+10	$kg\text{-}m^2$
I_{66}	2.42E+08	$kg\text{-}m^2$	I_{66}	1.35E-03	$kg\text{-}m^2$	I_{66}	2.42E+08	$kg\text{-}m^2$

Table B.15: System Natural Periods

System Natural Periods		
Surge	36.9	*sec*
Sway	36.9	*sec*
Heave	22.5	*sec*
Roll	32.5	*sec*
Pitch	32.5	*sec*
Yaw	18.4	*sec*

Table B.16: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	1.4	*deg*
Pitch	1.4	*deg*
Yaw	14.8	*deg*

Appendix C: Ring Pontoon Design Details

C.1 Design Iteration #1

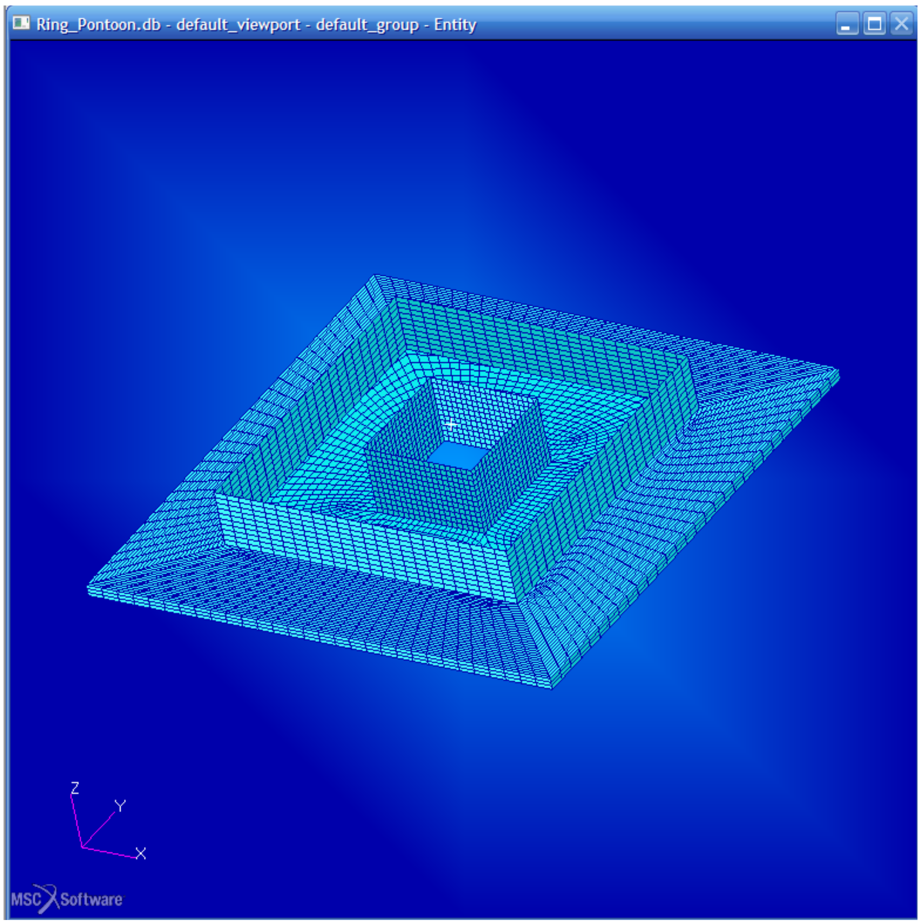


Figure C.1: Patran Model of Vessel

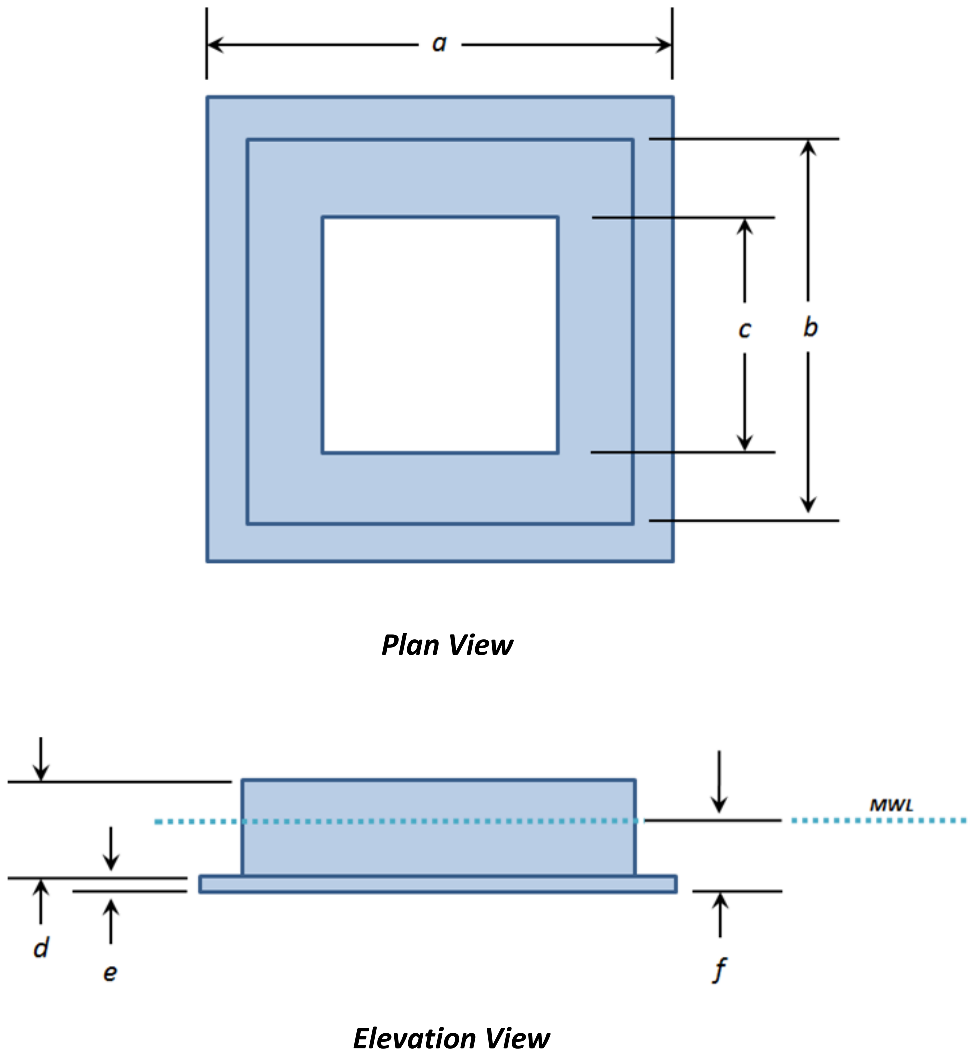


Figure C.2: Schematic of Vessel General Dimensions

Table C.1: Vessel General Dimensions and Displacement

Parameter			Value			
Pontoon	Pontoon length (outer)	***b***	**27**	*m*	90	*ft*
	Pontoon length (inner)	***c***	**10**	*m*	33	*ft*
	Pontoon height above skirt	***d***	**10**	*m*	33	*ft*
	Pontoon displaced volume		**3,890**	m^3	137,385	ft^3
Skirt	Skirt length	***a***	**44**	*m*	143	*ft*
	Skirt thickness	***e***	**1**	*m*	3	*ft*
	Skirt displaced volume		**1,148**	m^3	40,528	ft^3
Total Displaced Volume			**5,038**	m^3	177,913	ft^3

Draft	***f***	**6**	*m*	20	*ft*
Displacement		50,649	*kN*	**11,386**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**2.4**	*m*	8	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**9.2**	*m*	30	*ft*
Distance from Keel to Metacenter	***KM***	**12**	*m*	38	*ft*

Table C.2: Vessel Weight and Force Breakdown Groups

Parameter		Value			
Pontoon Steel		16,856	*kN*	**3,789**	*kips*
Special Steel		**1,686**	*kN*	379	*kips*
Pontoon Outfit and Equipment		**2,528**	*kN*	568	*kips*
Pontoon Subtotal		**21,070**	*kN*	4,737	*kips*
Skirt Steel		2,704	*kN*	**608**	*kips*
Special Steel		**270**	*kN*	61	*kips*
Skirt Outfit and Equipment		**406**	*kN*	91	*kips*
Skirt Subtotal		**3,380**	*kN*	760	*kips*
Deck Steel (basic structure)		**2,790**	*kN*	627	*kips*
Deck Steel (deck houses)		**0**	*kN*	0	*kips*
Special Steel		**0**	*kN*	0	*kips*
Rotor		**2,166**	*kN*	487	*kips*
Drivetrain		**2,923**	*kN*	657	*kips*
Add. Deck Equipment & Outfit - Marine & Support		**0**	*kN*	0	*kips*
Add. Deck Equipment & Outfit - Mission Systems		**491**	*kN*	110	*kips*
Topsides Subtotal		**8,370**	*kN*	1,882	*kips*
Other Hull Weight		**0**	*kN*	0	*kips*
Deck Reserve/Margin		**279**	*kN*	63	*kips*
Pontoon Fixed Ballast		**0**	*kN*	0	*kips*
LIGHTSHIP		**33,099**	*kN*	7,441	*kips*
Mooring Tension		**270**	*kN*	61	*kips*
Deck Variable Load		**0**	*kN*	0	*kips*
Column Variable Load		**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)		**17,280**	*kN*	3,885	*kips*
Subtotal External Load, Variable Load, and Ballast		**17,550**	*kN*	3,945	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE		**50,649**	*kN*	11,386	*kips*
Distance from Keel to Center of Gravity	***KG***	**7.5**	*m*	25	*ft*
Distance from Center of Gravity to Metacenter	***GM***	**4.1**	*m*	14	*ft*

Table C.3: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component CG and Mass				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2
Pontoon	Side 1 (East)	8.70	10.05	10.96	958	9.37	0.00	-0.48	287,713	5.37E+06	3.00E+07	2.95E+07	0.00E+00	0.00E+00	1.30E+06
	Side 2 (North)	10.05	8.70	10.96	958	0.00	9.37	-0.48	287,713	3.00E+07	5.37E+06	2.95E+07	0.00E+00	1.30E+06	0.00E+00
	Side 3 (West)	8.70	10.05	10.96	958	-9.37	0.00	-0.48	287,713	5.37E+06	3.00E+07	2.95E+07	0.00E+00	0.00E+00	-1.30E+06
	Side 4 (South)	10.05	8.70	10.96	958	0.00	-9.37	-0.48	287,713	3.00E+07	5.37E+06	2.95E+07	0.00E+00	-1.30E+06	0.00E+00
	Corner 1 (NE)	8.70	8.70	10.96	830	9.37	9.37	-0.48	249,240	2.60E+07	2.60E+07	4.70E+07	-2.19E+07	1.12E+06	1.12E+06
	Corner 2 (NW)	8.70	8.70	10.96	830	-9.37	9.37	-0.48	249,240	2.60E+07	2.60E+07	4.70E+07	2.19E+07	1.12E+06	-1.12E+06
	Corner 3 (SW)	8.70	8.70	10.96	830	-9.37	-9.37	-0.48	249,240	2.60E+07	2.60E+07	4.70E+07	-2.19E+07	-1.12E+06	-1.12E+06
	Corner 4 (SE)	8.70	8.70	10.96	830	9.37	-9.37	-0.48	249,240	2.60E+07	2.60E+07	4.70E+07	2.19E+07	-1.12E+06	1.12E+06
	Subtotal				7,154	0.00	0.00	-0.48	2,147,811	1.75E+08	1.75E+08	3.06E+08	0.00E+00	0.00E+00	0.00E+00
Skirt	Side 1 (East)	8.08	27.45	1.00	222	17.76	0.00	-5.46	66,561	6.17E+06	2.34E+07	2.55E+07	0.00E+00	0.00E+00	6.46E+06
	Side 2 (North)	27.45	8.08	1.00	222	0.00	17.76	-5.46	66,561	2.34E+07	6.17E+06	2.55E+07	0.00E+00	6.46E+06	0.00E+00
	Side 3 (West)	8.08	27.45	1.00	222	-17.76	0.00	-5.46	66,561	6.17E+06	2.34E+07	2.55E+07	0.00E+00	0.00E+00	-6.46E+06
	Side 4 (South)	27.45	8.08	1.00	222	0.00	-17.76	-5.46	66,561	2.34E+07	6.17E+06	2.55E+07	0.00E+00	-6.46E+06	0.00E+00
	Corner 1 (NE)	8.08	8.08	1.00	65	17.76	17.76	-5.46	19,581	6.87E+06	6.87E+06	1.26E+07	-6.18E+06	1.90E+06	1.90E+06
	Corner 2 (NW)	8.08	8.08	1.00	65	-17.76	17.76	-5.46	19,581	6.87E+06	6.87E+06	1.26E+07	6.18E+06	1.90E+06	-1.90E+06
	Corner 3 (SW)	8.08	8.08	1.00	65	-17.76	-17.76	-5.46	19,581	6.87E+06	6.87E+06	1.26E+07	-6.18E+06	-1.90E+06	-1.90E+06
	Corner 4 (SE)	8.08	8.08	1.00	65	17.76	-17.76	-5.46	19,581	6.87E+06	6.87E+06	1.26E+07	6.18E+06	-1.90E+06	1.90E+06
	Subtotal				1148	0.00	0.00	-5.46	344,568	8.65E+07	8.65E+07	1.52E+08	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	5.00	284,400	1.70E+07	1.70E+07	1.90E+07	0.00E+00	0.00E+00	0.00E+00
	Rotor	--	--	--	--	0.00	0.00	27.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	27.50	298,000	1.24E+09	1.27E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	27.50	50,000						
	Subtotal					0.00	0.00	20.00	853,200	1.26E+09	1.29E+09	5.38E+07	0.00E+00	0.00E+00	0.00E+00
Water Ballast	Side 1 (East)	8.70	10.05	2.63	230	9.37	0.00	-4.64	236,002	7.21E+06	2.75E+07	2.42E+07	0.00E+00	0.00E+00	1.03E+07
	Side 2 (North)	10.05	8.70	2.63	230	0.00	9.37	-4.64	236,002	2.75E+07	7.21E+06	2.42E+07	0.00E+00	1.03E+07	0.00E+00
	Side 3 (West)	8.70	10.05	2.63	230	-9.37	0.00	-4.64	236,002	7.21E+06	2.75E+07	2.42E+07	0.00E+00	0.00E+00	-1.03E+07
	Side 4 (South)	10.05	8.70	2.63	230	0.00	-9.37	-4.64	236,002	2.75E+07	7.21E+06	2.42E+07	0.00E+00	-1.03E+07	0.00E+00
	Column 1 (NE)	8.70	8.70	2.63	199	9.37	9.37	-4.64	204,444	2.38E+07	2.38E+07	3.85E+07	-1.80E+07	8.90E+06	8.90E+06
	Column 2 (NW)	8.70	8.70	2.63	199	-9.37	9.37	-4.64	204,444	2.38E+07	2.38E+07	3.85E+07	1.80E+07	8.90E+06	-8.90E+06
	Column 3 (SW)	8.70	8.70	2.63	199	-9.37	-9.37	-4.64	204,444	2.38E+07	2.38E+07	3.85E+07	-1.80E+07	-8.90E+06	-8.90E+06
	Column 4 (SE)	8.70	8.70	2.63	199	9.37	9.37	-4.64	204,444	2.38E+07	2.38E+07	3.85E+07	-1.80E+07	8.90E+06	8.90E+06
	Subtotal					0.00	2.18	-4.64	1,761,782	1.64E+08	1.64E+08	2.51E+08	-3.59E+07	1.78E+07	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	5.00	28,440	1.70E+06	1.70E+06	1.90E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	5.00	28,440	1.70E+06	1.70E+06	1.90E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						**0.00**	**0.75**	**1.19**	**5,135,801**	**1.68E+09**	**1.72E+09**	**7.65E+08**	**-3.59E+07**	**1.78E+07**	**0.00E+00**

Table C.4: Principal Mooring Details

Mooring Line	Fairlead Location			Pile Location			Line Length	Line Diameter	MBL	EA
	X	Y	Z	X	Y	Z				
#	m	m	m	m	m	m	m	mm	kN	kN
1	23.0	-20.0	-6.0	400.0	0.0	-150.0	403.6	60	1000	15,000
2	23.0	20.0	-6.0	400.0	0.0	-150.0	403.6	60	1000	15,000
3	20.0	23.0	-6.0	0.0	400.0	-150.0	403.6	60	1000	15,000
4	-20.0	23.0	-6.0	0.0	400.0	-150.0	403.6	60	1000	15,000
5	-23.0	20.0	-6.0	-400.0	0.0	-150.0	403.6	60	1000	15,000
6	-23.0	-20.0	-6.0	-400.0	0.0	-150.0	403.6	60	1000	15,000
7	-20.0	-23.0	-6.0	0.0	-400.0	-150.0	403.6	60	1000	15,000
8	20.0	-23.0	-6.0	0.0	-400.0	-150.0	403.6	60	1000	15,000

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness (15×MBL)

Table C.5: Principal Vessel and Mooring Stiffness Values

Vessel Hydrostatic Stiffness			Mooring System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	1.33E+05	*N/m*	K_{11}	1.33E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	1.33E+05	*N/m*	K_{22}	1.33E+05	*N/m*
K_{33}	6.56E+06	*N/m*	K_{33}	3.51E+04	*N/m*	K_{33}	6.60E+06	*N/m*
K_{44}	3.62E+06	*(N-m)/deg*	K_{44}	3.53E+05	*(N-m)/deg*	K_{44}	3.98E+06	*(N-m)/deg*
K_{55}	3.62E+06	*(N-m)/deg*	K_{55}	3.53E+05	*(N-m)/deg*	K_{55}	3.98E+06	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	1.08E+06	*(N-m)/deg*	K_{66}	1.08E+06	*(N-m)/deg*

Table C.6: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	5.14E+06	*kg*	M_{11}	3.59E+06	*kg*	M_{11}	8.73E+06	*kg*
M_{22}	5.14E+06	*kg*	M_{22}	3.59E+06	*kg*	M_{22}	8.73E+06	*kg*
M_{33}	5.14E+06	*kg*	M_{33}	2.85E+07	*kg*	M_{33}	3.36E+07	*kg*
I_{44}	1.68E+09	*kg-m²* → $kg\text{-}m^2$	I_{44}	4.00E+09	$kg\text{-}m^2$	I_{44}	5.68E+09	$kg\text{-}m^2$
I_{55}	1.72E+09	$kg\text{-}m^2$	I_{55}	4.00E+09	$kg\text{-}m^2$	I_{55}	5.71E+09	$kg\text{-}m^2$
I_{66}	7.65E+08	$kg\text{-}m^2$	I_{66}	1.64E+08	$kg\text{-}m^2$	I_{66}	9.29E+08	$kg\text{-}m^2$

Table C.7: System Natural Periods

System Natural Periods		
Surge	50.9	*sec*
Sway	50.9	*sec*
Heave	14.2	*sec*
Roll	31.4	*sec*
Pitch	31.5	*sec*
Yaw	24.4	*sec*

Table C.8: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	19.9	*deg*
Pitch	19.9	*deg*
Yaw	6.8	*deg*

Appendix D: Compact Semi-Submersible Design Details

D.1 Design Iteration #1

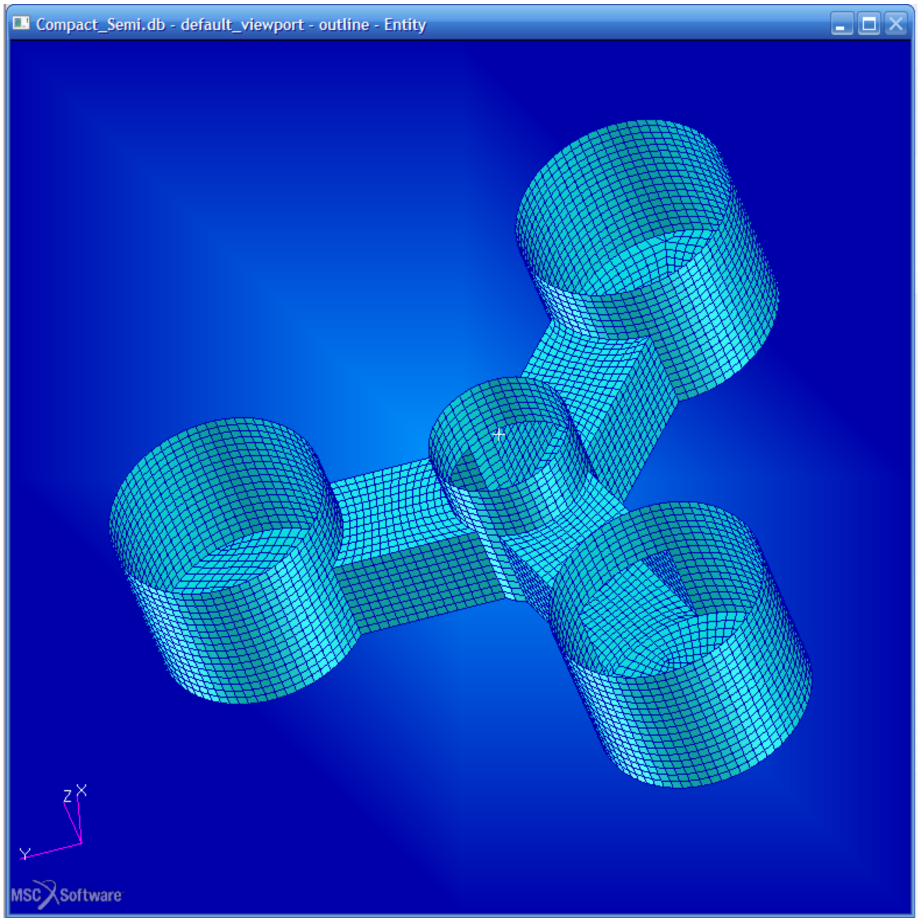


Figure D.1: Patran Model of Vessel

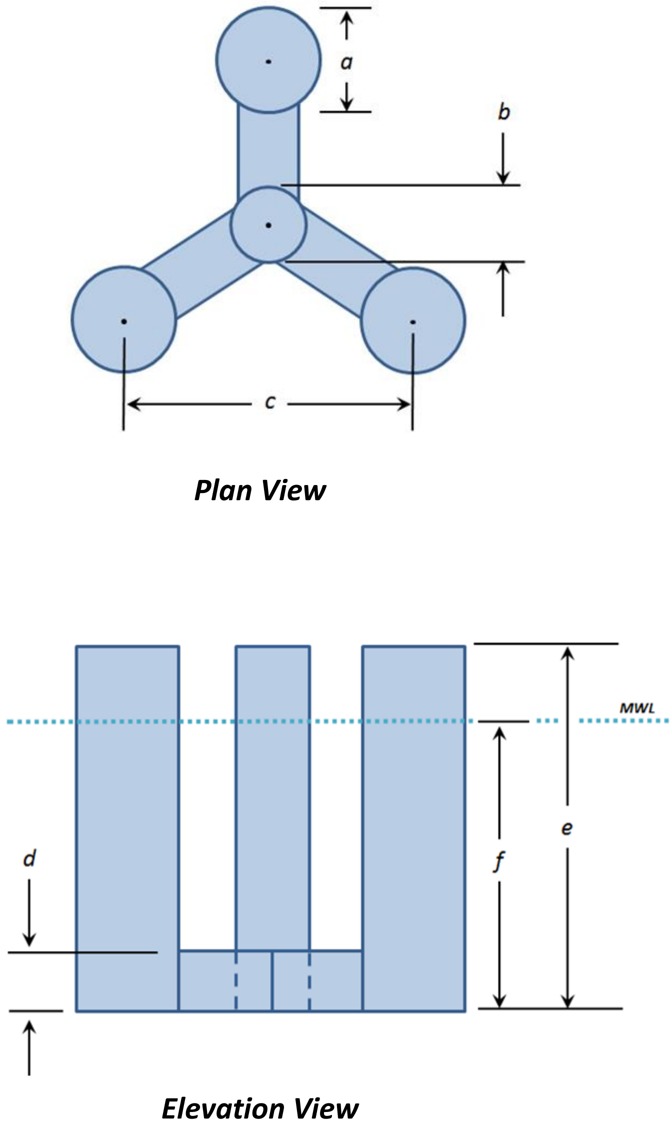


Figure D.2: Schematic of Vessel General Dimension

Table D.1: Vessel General Dimensions and Displacement

Parameter			Value			
Pontoon	Column-base pontoon spacing	***c***	**25**	*m*	83	*ft*
	Planview area of pontoons		**105**	m^2	1,132	ft^2
	Connecting pontoon height	***d***	**7**	*m*	22	*ft*
	Displaced volume of pontoons		**698**	m^3	24,664	ft^3
Column	Center column diameter	***b***	**7**	*m*	23	*ft*
	Outer column diameter	***a***	**12**	*m*	39	*ft*
	Column height	***e***	**16**	*m*	51	*ft*
	Water plane area		**379**	m^2	4,075	ft^2
	Displaced volume of columns		**4,028**	m^3	142,226	ft^3
Total Displaced Volume			**4,726**	m^3	166,890	ft^3

Draft	***f***	**11**	*m*	35	*ft*
Displacement		47,511	*kN*	**10,681**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**5.0**	*m*	16	*ft*
Distance from CB to Metacenter	***BM***	**8.3**	*m*	27	*ft*
Distance from Keel to Metacenter	***KM***	**13**	*m*	44	*ft*

Table D.2: Vessel Weight and Force Breakdown Groups

Parameter		Value			
Pontoon Steel		1,646	*kN*	**370**	*kips*
Special Steel		**165**	*kN*	37	*kips*
Pontoon Outfit and Equipment		**247**	*kN*	55	*kips*
Pontoon Subtotal		**2,057**	*kN*	462	*kips*
Center Column Steel		1,421	*kN*	**319**	*kips*
Special Steel		**426**	*kN*	96	*kips*
Column Outfit and Equipment		**213**	*kN*	48	*kips*
Center Column Subtotal		**2,060**	*kN*	463	*kips*
Outer Columns Steel		12,529	*kN*	**2,817**	*kips*
Special Steel		3,759	*kN*	845	*kips*
Column Outfit and Equipment		1,879	*kN*	422	*kips*
Outer Column Subtotal		18,167	*kN*	4,084	*kips*
Deck Steel (basic structure)		**1,674**	*kN*	376	*kips*
Deck Steel (deck houses)		**0**	*kN*	0	*kips*
Special Steel		**0**	*kN*	0	*kips*
Rotor		**2,166**	*kN*	487	*kips*
Drivetrain		**2,923**	*kN*	657	*kips*
Add'l Deck Equipment & Outfit - Marine & Support		**0**	*kN*	0	*kips*
Add'l Deck Equipment & Outfit - Mission Systems		**491**	*kN*	110	*kips*
Topsides Subtotal		**7,254**	*kN*	1,631	*kips*
Other Hull Weight		**0**	***kN***	**0**	***kips***
Deck Reserve/Margin		**167**	***kN***	**38**	***kips***
Pontoon Fixed Ballast		**0**	***kN***	**0**	***kips***
LIGHTSHIP		**29,705**	***kN***	**6,678**	***kips***
Mooring Tension		**270**	*kN*	61	*kips*
Deck Variable Load		**0**	*kN*	0	*kips*
Column Variable Load		**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)		**17,536**	*kN*	3,942	*kips*
Subtotal External Load, Variable Load & Ballast		**17,806**	*kN*	4,003	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE		**47,511**	*kN*	10,681	*kips*

Distance from Keel to Center of Gravity	***KG***	**9.4**	*m*	31	*ft*
Distance from Center of Gravity to Metacenter	***GM***	**4.0**	*m*	13	*ft*

Table D.3: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component CG and Mass				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2
Pontoon	Pontoon 1	--	--	6.64	233	5.23	-3.02	-7.32	69,897	4.84E+06	6.11E+06	2.91E+06	1.11E+06	-1.55E+06	2.68E+06
	Pontoon 2	--	--	6.64	233	0.00	6.04	-7.32	69,897	6.71E+06	4.21E+06	2.91E+06	0.00E+00	3.09E+06	0.00E+00
	Pontoon 3	--	--	6.64	233	-5.23	-3.02	-7.32	69,897	4.38E+06	5.66E+06	2.91E+06	-1.11E+06	-1.55E+06	-2.68E+06
	Subtotal					0.00	0.00	-7.32	209,692	1.59E+07	1.60E+07	8.74E+06	0.00E+00	0.00E+00	0.00E+00
Column	Center Column 1	--	--	15.64	603	0.00	0.00	-2.82	209,988	6.59E+06	6.59E+06	1.29E+06	0.00E+00	0.00E+00	0.00E+00
	Outer Column 1	--	--	15.64	1,772	12.64	-7.30	-2.82	617,293	5.59E+07	1.22E+08	1.43E+08	5.69E+07	-1.27E+07	2.20E+07
	Outer Column 2	--	--	15.64	1,772	0.00	14.59	-2.82	617,293	1.54E+08	2.31E+07	1.43E+08	0.00E+00	2.54E+07	0.00E+00
	Outer Column 3	--	--	15.64	1,772	-12.64	-7.30	-2.82	617,293	5.59E+07	1.22E+08	1.43E+08	-5.69E+07	-1.27E+07	-2.20E+07
	Subtotal					0.00	0.00	-2.82	2,061,868	2.73E+08	2.73E+08	4.29E+08	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	5.00	170,640	1.02E+07	1.02E+07	1.14E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	27.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	27.50	298,000	1.24E+09	1.27E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	27.50	50,000						
	Subtotal					0.00	0.00	22.31	739,440	1.25E+09	1.28E+09	4.62E+07	0.00E+00	0.00E+00	0.00E+00
Water Ballast	Pontoon 1	--	--	--	--	5.23	-3.02	-7.32	238,631	1.50E+07	1.93E+07	8.72E+06	3.77E+06	-5.28E+06	9.14E+06
	Pontoon 2	--	--	--	--	0.00	6.04	-7.32	238,631	2.15E+07	1.28E+07	8.72E+06	0.00E+00	1.06E+07	0.00E+00
	Pontoon 3	--	--	--	--	-5.23	-3.02	-7.32	238,631	1.50E+07	1.93E+07	8.72E+06	-3.77E+06	-5.28E+06	-9.14E+06
	Center Column 1	--	--	2.76	--	0.00	0.00	-9.26	109,142	9.76E+06	9.76E+06	6.70E+05	0.00E+00	0.00E+00	0.00E+00
	Outer Column 1	--	--	2.76	--	12.64	-7.30	-9.26	320,840	4.77E+07	8.18E+07	7.41E+07	2.96E+07	-2.17E+07	3.75E+07
	Outer Column 2	--	--	2.76	--	0.00	14.59	-9.26	320,840	9.89E+07	3.06E+07	7.41E+07	0.00E+00	4.33E+07	0.00E+00
	Outer Column 3	--	--	2.76	--	-12.64	-7.30	-9.26	320,840	4.77E+07	8.18E+07	7.41E+07	-2.96E+07	-2.17E+07	-3.75E+07
	Subtotal					0.00	0.00	-8.48	1,787,556	2.55E+08	2.55E+08	2.49E+08	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	5.00	17,064	1.02E+06	1.02E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	5.00	17,064	1.02E+06	1.02E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						**0.00**	**0.00**	**-1.23**	**4,815,620**	**1.79E+09**	**1.83E+09**	**7.34E+08**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table D.4: Principal Mooring Details

Mooring Line #	Fairlead Location X m	Fairlead Location Y m	Fairlead Location Z m	Pile Location X m	Pile Location Y m	Pile Location Z m	Line Length m	Line Diameter mm	MBL kN	EA kN
1	0.00	23.00	-9.00	346.41	200.0	-150.0	399.7	60	1000	15,000
2	0.00	23.00	-9.00	0.00	400.0	-150.0	399.7	60	1000	15,000
3	0.00	23.00	-9.00	-346.41	200.0	-150.0	399.7	60	1000	15,000
4	-19.92	-11.50	-9.00	-346.41	200.0	-150.0	399.7	60	1000	15,000
5	-19.92	-11.50	-9.00	-346.41	-200.0	-150.0	399.7	60	1000	15,000
6	-19.92	-11.50	-9.00	0.00	-400.0	-150.0	399.7	60	1000	15,000
7	19.92	-11.50	-9.00	0.00	-400.0	-150.0	399.7	60	1000	15,000
8	19.92	-11.50	-9.00	346.41	-200.0	-150.0	399.7	60	1000	15,000
9	19.92	-11.50	-9.00	346.41	200.0	-150.0	399.7	60	1000	15,000

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness (15×MBL)

Table D.5: Principal Vessel and Mooring Stiffness Values

Vessel Hydrostatic Stiffness			Mooring System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	1.59E+05	*N/m*	K_{11}	1.59E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	1.59E+05	*N/m*	K_{22}	1.59E+05	*N/m*
K_{33}	3.80E+06	*N/m*	K_{33}	2.73E+04	*N/m*	K_{33}	3.83E+06	*N/m*
K_{44}	3.26E+06	*(N-m)/deg*	K_{44}	2.27E+05	*(N-m)/deg*	K_{44}	3.49E+06	*(N-m)/deg*
K_{55}	3.26E+06	*(N-m)/deg*	K_{55}	2.27E+05	*(N-m)/deg*	K_{55}	3.49E+06	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	1.65E+06	*(N-m)/deg*	K_{66}	1.65E+06	*(N-m)/deg*

Table D.6: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	4.82E+06	*kg*	M_{11}	3.74E+06	*kg*	M_{11}	8.56E+06	*kg*
M_{22}	4.82E+06	*kg*	M_{22}	3.74E+06	*kg*	M_{22}	8.56E+06	*kg*
M_{33}	4.82E+06	*kg*	M_{33}	3.14E+06	*kg*	M_{33}	7.96E+06	*kg*
I_{44}	1.93E+01	*kg-m²*	I_{44}	5.35E+04	*kg-m²*	I_{44}	5.35E+04	*kg-m²*
I_{55}	1.95E+01	*kg-m²*	I_{55}	-5.79E+04	*kg-m²*	I_{55}	-5.79E+04	*kg-m²*
I_{66}	1.23E+01	*kg-m²*	I_{66}	5.71E+08	*kg-m²*	I_{66}	5.71E+08	*kg-m²*

Table D.7: System Natural Periods

System Natural Periods		
Surge	46.1	*sec*
Sway	46.1	*sec*
Heave	9.1	*sec*
Roll	18.8	*sec*
Pitch	19.0	*sec*
Yaw	23.3	*sec*

Table D.8: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	22.8	*deg*
Pitch	22.8	*deg*
Yaw	4.4	*deg*

Appendix E: Advanced Spar Design Details

E.1 Design Iteration #1

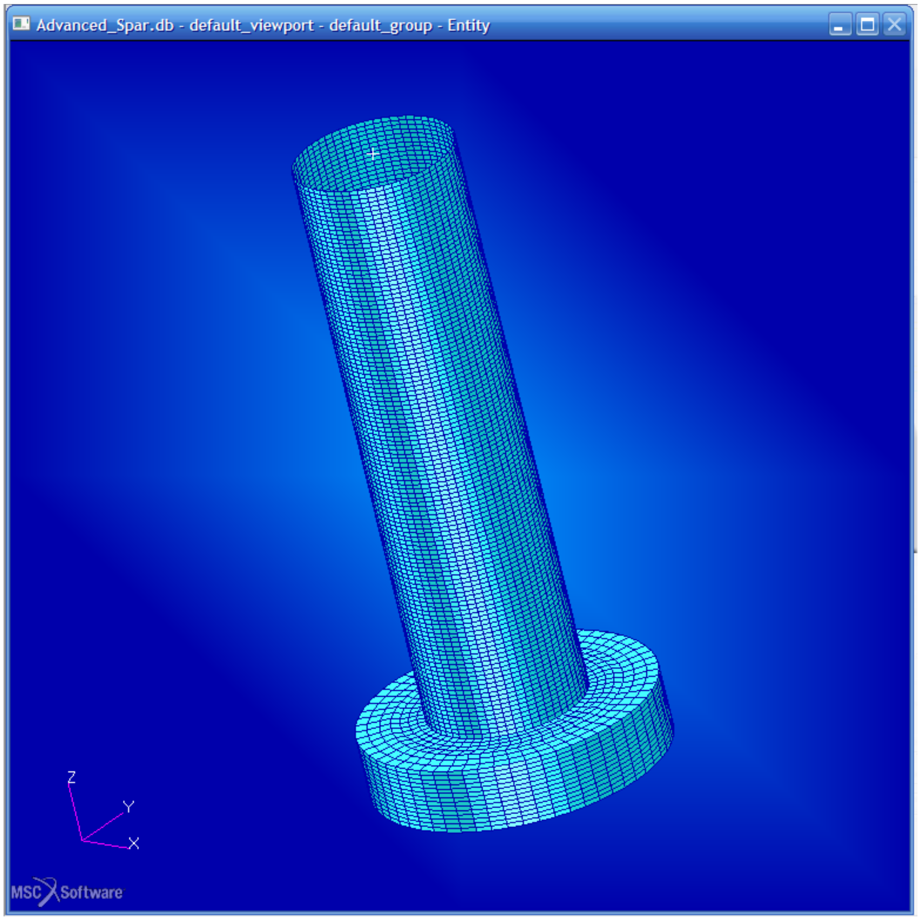
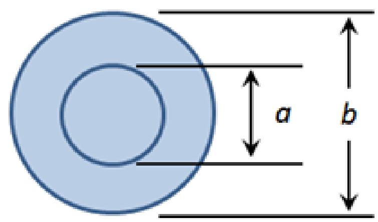
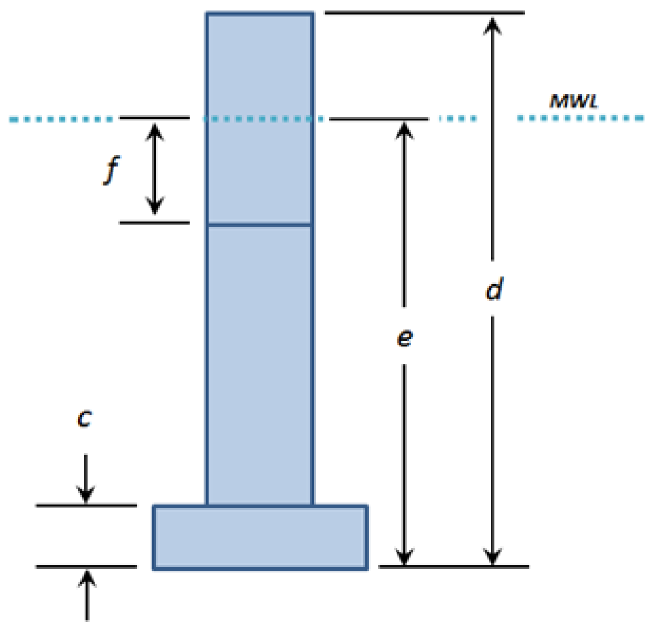


Figure E.1: Patran Model of Vessel



Plan View



Elevation View

Figure E.2: Schematic of Vessel General Dimension

Table E.1: Vessel General Dimensions and Displacement

Parameter			Value			
Column	Spar diameter	***a***	**17**	*m*	56	*ft*
	Spar submerged depth		**44**	*m*	144	*ft*
	Spar height (wrt top)	***d***	**55**	*m*	180	*ft*
	Hard tank draft	***f***	**20**	*m*	66	*ft*
	Water plane area		**232**	m^2	2,502	ft^2
Pontoon	Pontoon diameter	***b***	**32**	*m*	105	*ft*
	Pontoon height	***c***	**6**	*m*	21	*ft*
	Pontoon area		**804**	m^2	8,657	ft^2
Displaced Volumes	Hard tank (void)		**3,694**	m^3	130,455	ft^3
	Hard tank (variable)		**971**	m^3	34,300	ft^3
	Mid-section		**5,504**	m^3	194,357	ft^3
	Soft tank (Pontoon)		**5,031**	m^3	177,648	ft^3
	Total displaced volume		**15,200**	m^3	536,760	ft^3

Draft	***e***	**50**	*m*	164	*ft*
Displacement		152,808	*kN*	**34,353**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**20**	*m*	65	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**0.283**	*m*	1	*ft*
Distance from Keel to Metacenter	***KM***	**20**	*m*	66	*ft*

Table E.2: Vessel Weight and Force Breakdown Groups

Parameter	Value			
Hard Tank Steel	**7,311**	*kN*	1,644	*kips*
Mid-section Steel	**5,021**	*kN*	1,129	*kips*
Pontoon/Soft Tank Steel	**4,935**	*kN*	1,109	*kips*
Spar Hull Steel Subtotal	**17,267**	*kN*	3,882	*kips*
Special Steel	**1,727**	*kN*	388	*kips*
Spar Hull Outfit and Equipment	**2,590**	*kN*	582	*kips*
Spar Hull Subtotal	**21,584**	*kN*	4,852	*kips*
Deck Steel (basic structure)	7,842	*kN*	**1,763**	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add'l Deck Equipment & Outfit - Marine & Support	**0**	*kN*	0	*kips*
Add'l Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**13,422**	*kN*	3,017	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**784**	*kN*	176	*kips*
Hull Fixed Ballast	**10,738**	*kN*	2,414	*kips*
LIGHTSHIP	**46,528**	*kN*	10,460	*kips*
Mooring Tension	**270**	*kN*	61	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (column)	**3,521**	*kN*	792	*kips*
Entrained Water (mid-section)	**55,342**	*kN*	12,441	*kips*
Entrained Water (soft tank)	**47,147**	*kN*	10,599	*kips*
Subtotal External Load, Variable Load, and Ballast	**106,280**	*kN*	852	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**152,808**	*kN*	11,312	*kips*

Distance from Keel to Center of Gravity	***KG***	**18**	*m*	58	*ft*
Distance from Center of Gravity to Metacenter	***GM***	**2.48**	*m*	8	*ft*

Table E.3: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component CG and Mass				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2
Spar Hull	Hard Tank (Void)	--	--	20.89	4,857	0.00	0.00	-5.45	776,292	6.56E+07	6.56E+07	2.87E+07	0.00E+00	0.00E+00	0.00E+00
	Hard Tank (Variable)	--	--	4.18	971	0.00	0.00	-17.98	155,258	5.33E+07	5.33E+07	5.74E+06	0.00E+00	0.00E+00	0.00E+00
	Mid-section Steel	--	--	23.68	--	0.00	0.00	-31.91	639,814	6.93E+08	6.93E+08	2.37E+07	0.00E+00	0.00E+00	0.00E+00
	Soft Tank (Pontoon)	--	--	6.26	5,031	0.00	0.00	-46.87	628,826	1.40E+09	1.40E+09	2.33E+07	0.00E+00	0.00E+00	0.00E+00
	Sub Total					0.00	0.00	-25.87	2,200,190	2.21E+09	2.21E+09	8.14E+07	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	5.00	799,410	4.77E+07	4.77E+07	5.33E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	27.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	27.50	298,000	1.24E+09	1.27E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	27.50	50,000						
	Sub Total					0.00	0.00	14.35	1,368,210	1.29E+09	1.32E+09	8.81E+07	0.00E+00	0.00E+00	0.00E+00
Ballast	Fixed Ballast	--	--	0.42	342	0.00	0.00	-49.79	1,094,568	2.73E+09	2.73E+09	4.05E+07	0.00E+00	0.00E+00	0.00E+00
	Variable Ballast	--	--	1.51	350	0.00	0.00	-19.32	358,919	1.41E+08	1.41E+08	1.33E+07	0.00E+00	0.00E+00	0.00E+00
	Sub Total					0.00	0.00	-42.26	1,453,488	2.87E+09	2.87E+09	5.38E+07	0.00E+00	0.00E+00	0.00E+00
Entrained Water	Mid-section	--	--	23.68	5,504	0.00	0.00	-31.91	5,641,365	6.11E+09	6.11E+09	2.09E+08	0.00E+00	0.00E+00	0.00E+00
	Soft Tank	--	--	5.83	4,689	0.00	0.00	-46.66	4,806,043	1.06E+10	1.06E+10	1.78E+08	0.00E+00	0.00E+00	0.00E+00
	Sub Total					0.00	0.00	-38.69	1.04E+07	1.67E+10	1.67E+10	3.87E+08	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	5.00	79,941	4.77E+06	4.77E+06	5.33E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Sub Total					0.00	0.00	5.00	79,941	4.77E+06	4.77E+06	5.33E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						**0.00**	**0.00**	**-32.32**	**1.55E+07**	**2.30E+10**	**2.31E+10**	**6.15E+08**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table E.4: Principal Mooring Details

Mooring Line #	Fairlead Location X m	Fairlead Location Y m	Fairlead Location Z m	Pile Location X m	Pile Location Y m	Pile Location Z m	Line Length m	Line Diameter mm	MBL kN	EA kN
1	15.0	-15.0	-30.0	400.0	0.0	-150.0	403.3	60	1000	15,000
2	15.0	15.0	-30.0	400.0	0.0	-150.0	403.3	60	1000	15,000
3	15.0	15.0	-30.0	0.0	400.0	-150.0	403.3	60	1000	15,000
4	-15.0	15.0	-30.0	0.0	400.0	-150.0	403.3	60	1000	15,000
5	-15.0	15.0	-30.0	-400.0	0.0	-150.0	403.3	60	1000	15,000
6	-15.0	-15.0	-30.0	-400.0	0.0	-150.0	403.3	60	1000	15,000
7	-15.0	-15.0	-30.0	0.0	-400.0	-150.0	403.3	60	1000	15,000
8	15.0	-15.0	-30.0	0.0	-400.0	-150.0	403.3	60	1000	15,000

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness (15×MBL)

Table E.5: Principal Vessel and Mooring Stiffness Values

Vessel Hydrostatic Stiffness			Mooring System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	1.38E+05	*N/m*	K_{11}	1.38E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	1.38E+05	*N/m*	K_{22}	1.38E+05	*N/m*
K_{33}	2.33E+06	*N/m*	K_{33}	2.87E+04	*N/m*	K_{33}	2.36E+06	*N/m*
K_{44}	7.22E+06	*(N-m)/deg*	K_{44}	1.89E+06	*(N-m)/deg*	K_{44}	9.12E+06	*(N-m)/deg*
K_{55}	7.22E+06	*(N-m)/deg*	K_{55}	1.89E+06	*(N-m)/deg*	K_{55}	9.12E+06	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	1.38E+06	*(N-m)/deg*	K_{66}	1.38E+06	*(N-m)/deg*

Table E.6: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	1.55E+07	*kg*	M_{11}	1.70E+07	*kg*	M_{11}	3.25E+07	*kg*
M_{22}	1.55E+07	*kg*	M_{22}	1.70E+07	*kg*	M_{22}	3.25E+07	*kg*
M_{33}	1.55E+07	*kg*	M_{33}	1.06E+07	*kg*	M_{33}	2.61E+07	*kg*
I_{44}	2.30E+10	*kg-m*^{2}	I_{44}	2.97E+10	*kg-m*^{2}	I_{44}	5.28E+10	*kg-m*^{2}
I_{55}	2.31E+10	*kg-m*^{2}	I_{55}	2.97E+10	*kg-m*^{2}	I_{55}	5.28E+10	*kg-m*^{2}
I_{66}	6.15E+08	*kg-m*^{2}	I_{66}	7.77E-02	*kg-m*^{2}	I_{66}	6.15E+08	*kg-m*^{2}

Table E.7: System Natural Periods

System Natural Periods		
Surge	96.4	*sec*
Sway	96.4	*sec*
Heave	20.9	*sec*
Roll	63.1	*sec*
Pitch	63.2	*sec*
Yaw	17.5	*sec*

Table E.8: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	8.7	*deg*
Pitch	8.7	*deg*
Yaw	5.3	*deg*

Appendix F: Multi-cellular Tension Leg Platform Design Details

F.1 Design Iteration #1

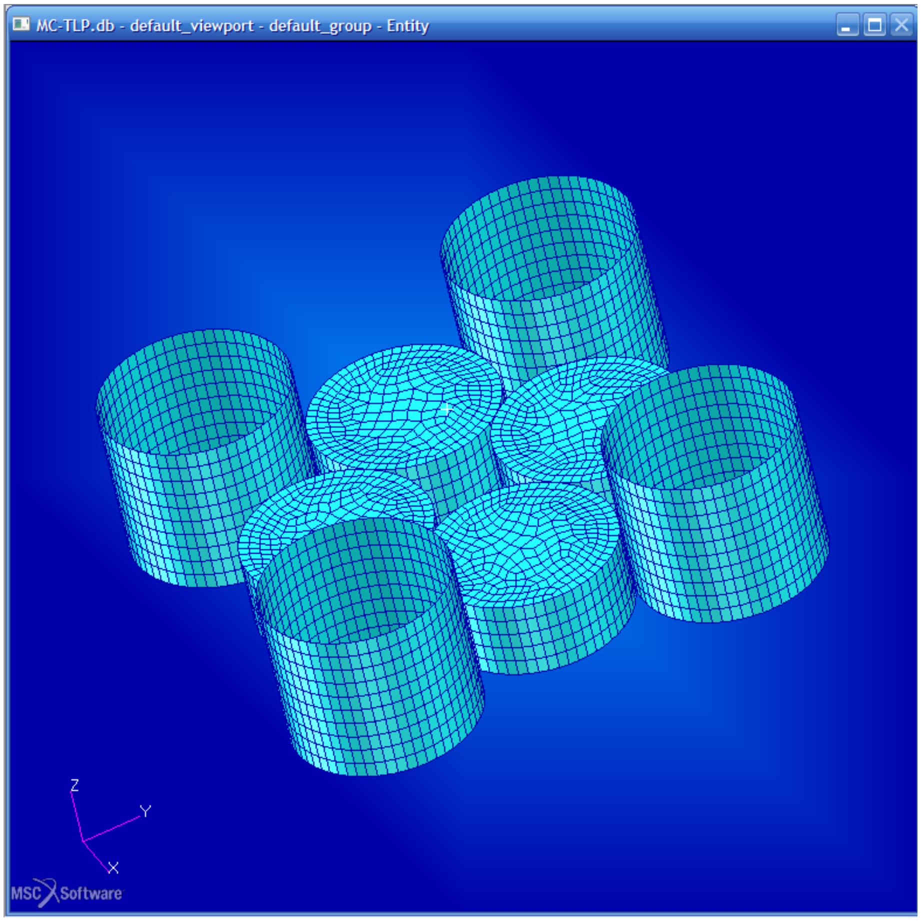
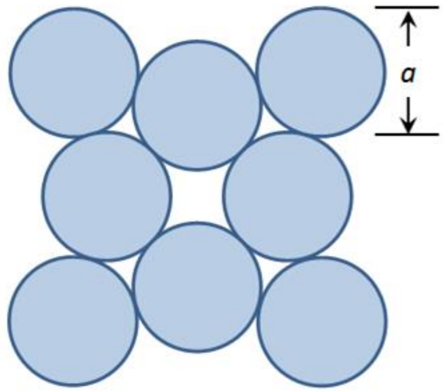
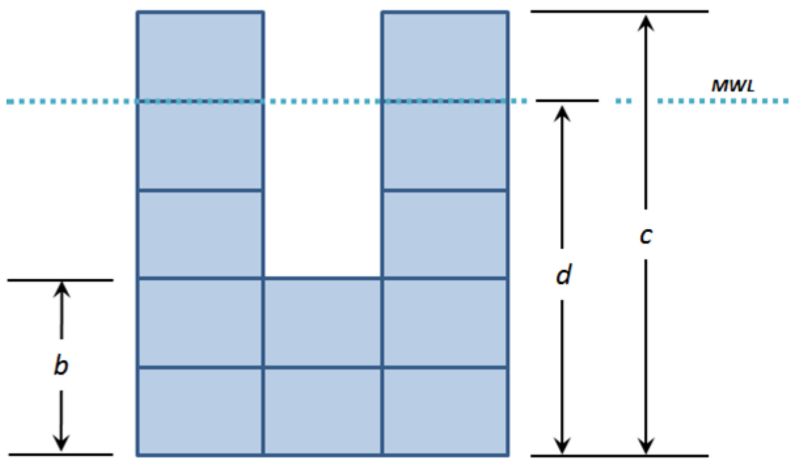


Figure F.1: Patran Model of Vessel



Plan View



Elevation View

Figure F.2: Schematic of Vessel General Dimensions

Table F.1: Vessel General Dimensions and Displacement

Parameter			Value			
Pontoon	Pontoon Cell diameter		**11.6**	*m*	38	*ft*
	Pontoon Cell cross-section		**105.8**	m^2	1,139	ft^2
	Pontoon Height	***b***	**4.86**	*m*	16	*ft*
	Displaced volume of pontoons		**2,058**	m^3	72,675	ft^3
Column	Column Cell diameter	***a***	**11.6**	*m*	38	*ft*
	Column Cell cross-section		**106**	m^2	1,139	ft^2
	Column height	***c***	**20**	*m*	65	*ft*
	Displaced volume of columns		**4,116**	m^3	145,351	ft^3
	Water plane area		**423**	m^2	4,555	ft^2
Total Displaced Volume			**6,174**	m^3	218,026	ft^3

Draft	***d***	**10**	*m*	32	*ft*
Displacement		62,069	*kN*	**13,954**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**4.1**	*m*	13	*ft*
Distance from CB to Metacenter	***BM***	**9.2**	*m*	30	*ft*
Distance from Keel to Metacenter	***KM***	**13**	*m*	43	*ft*

Table F.2: Vessel Weight and Force Breakdown Groups

Parameter	Value			
Pontoon Steel	4,849	*kN*	**1,090**	*kips*
Special Steel	**485**	*kN*	109	*kips*
Pontoon Outfit and Equipment	**727**	*kN*	164	*kips*
Pontoon Subtotal	**6,061**	*kN*	1,363	*kips*
Column Steel	19,669	*kN*	**4,422**	*kips*
Special Steel	**1,967**	*kN*	442	*kips*
Column Outfit and Equipment	**2,950**	*kN*	663	*kips*
Column Subtotal	**24,586**	*kN*	5,527	*kips*
Deck Steel (basic structure)	**1,674**	*kN*	376	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add’l Deck Equipment & Outfit - Marine & Support	**0**	*kN*	0	*kips*
Add’l Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**7,254**	*kN*	1,631	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**167**	*kN*	38	*kips*
Pontoon Fixed Ballast	**0**	*kN*	0	*kips*
LIGHTSHIP	**38,069**	*kN*	8,558	*kips*
Mooring Tension	**24,000**	*kN*	5,395	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)	**0**	*kN*	0	*kips*
Subtotal External Load, Variable Load, and Ballast	**24,000**	*kN*	5,395	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**62,069**	*kN*	13,954	*kips*

Distance from Keel to Center of Gravity	***KG***	**8.9**	*m*	29	*ft*
Distance from CG to Metacenter	***GM***	**4.3**	*m*	14	*ft*

Table F.3: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component CG and Mass				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2
Pontoon	Pontoon 1 (East)	--	--	4.86	515	8.207	0.00	-7.30	154,470	9.83E+06	2.02E+07	1.30E+07	0.00E+00	0.00E+00	9.25E+06
	Pontoon 2 (North)	--	--	4.86	515	0.00	8.207	-7.30	154,470	2.02E+07	9.83E+06	1.30E+07	0.00E+00	9.25E+06	0.00E+00
	Pontoon 3 (West)	--	--	4.86	515	-8.207	0.00	-7.30	154,470	9.83E+06	2.02E+07	1.30E+07	0.00E+00	0.00E+00	-9.25E+06
	Pontoon 4 (South)	--	--	4.86	515	0.00	-8.207	-7.30	154,470	2.02E+07	9.83E+06	1.30E+07	0.00E+00	-9.25E+06	0.00E+00
	Subtotal					0.00	0.00	-7.30	617,882	6.01E+07	6.01E+07	5.20E+07	0.00E+00	0.00E+00	0.00E+00
Column	Column 1 (NE)	--	--	19.73	8,348	11.210	11.210	0.14	626,561	1.04E+08	1.04E+08	1.68E+08	-7.87E+07	-9.60E+05	-9.60E+05
	Column 2 (NW)	--	--	19.73	8,348	-11.210	11.210	0.14	626,561	1.04E+08	1.04E+08	1.68E+08	7.87E+07	-9.60E+05	9.60E+05
	Column 3 (SW)	--	--	19.73	8,348	-11.210	-11.210	0.14	626,561	1.04E+08	1.04E+08	1.68E+08	-7.87E+07	9.60E+05	9.60E+05
	Column 4 (SE)	--	--	19.73	8,348	11.210	-11.210	0.14	626,561	1.04E+08	1.04E+08	1.68E+08	7.87E+07	9.60E+05	-9.60E+05
	Subtotal					0.00	0.00	0.14	2,506,242	4.17E+08	4.17E+08	6.72E+08	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	10.00	170,640	2.30E+07	2.30E+07	1.14E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	32.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	32.50	298,000	1.41E+09	1.44E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	32.50	50,000						
	Subtotal					0.00	0.00	27.31	739,440	1.43E+09	1.46E+09	4.62E+07	0.00E+00	0.00E+00	0.00E+00
Pontoon Fixed Ballast	Pontoon 1 (East)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 2 (North)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 3 (West)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 4 (South)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal									--	--	--	--	--	--
Water Ballast	Pontoon 1 (East)	--	--	4.86	0	8.207	0.00	-9.73	0	2.68E-01	4.39E-01	2.15E-01	0.00E+00	0.00E+00	2.03E-01
	Pontoon 2 (North)	--	--	4.86	0	0.00	8.207	-9.73	0	4.39E-01	2.68E-01	2.15E-01	0.00E+00	2.03E-01	0.00E+00
	Pontoon 3 (West)	--	--	4.86	0	-8.207	0.00	-9.73	0	2.68E-01	4.39E-01	2.15E-01	0.00E+00	0.00E+00	-2.03E-01
	Pontoon 4 (South)	--	--	4.86	0	0.00	-8.207	-9.73	0	4.39E-01	2.68E-01	2.15E-01	0.00E+00	-2.03E-01	0.00E+00
	Column 1 (NE)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Column 2 (NW)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Column 3 (SW)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Column 4 (SE)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	-9.73	0	1.41E+00	1.41E+00	8.58E-01	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	10.00	17,064	2.30E+06	2.30E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	10.00	17,064	2.30E+06	2.30E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						**0.00**	**0.00**	**4.17**	**3,880,629**	**1.91E+09**	**1.94E+09**	**7.71E+08**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table F.4: Principal Tendon Details

Tendon	Fairlead Location			Pile Location			Line Length	Line Diameter	MBL	EA
	X	Y	Z	X	Y	Z				
#	m	m	m	m	m	m	m	mm	kN	kN
1	17.0	14.0	-4.0	17.0	14.0	-150.0	146.0	114	12,775	1222
2	14.0	17.0	-4.0	14.0	17.0	-150.0	146.0	114	12,775	1222
3	-14.0	17.0	-4.0	-14.0	17.0	-150.0	146.0	114	12,775	1222
4	-17.0	14.0	-4.0	-17.0	14.0	-150.0	146.0	114	12,775	1222
5	-17.0	-14.0	-4.0	-17.0	-14.0	-150.0	146.0	114	12,775	1222
6	-14.0	-17.0	-4.0	-14.0	-17.0	-150.0	146.0	114	12,775	1222
7	14.0	-17.0	-4.0	14.0	-17.0	-150.0	146.0	114	12,775	1222
8	17.0	-14.0	-4.0	17.0	-14.0	-150.0	146.0	114	12,775	1222

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness

Table F.5: Principal Vessel and Tendon Stiffness Values

Vessel Hydrostatic Stiffness			Tendon System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	1.62E+05	*N/m*	K_{11}	1.62E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	1.62E+05	*N/m*	K_{22}	1.62E+05	*N/m*
K_{33}	4.25E+06	*N/m*	K_{33}	6.69E+07	*N/m*	K_{33}	7.12E+07	*N/m*
K_{44}	1.03E+06	*(N-m)/deg*	K_{44}	2.85E+08	*(N-m)/deg*	K_{44}	2.86E+08	*(N-m)/deg*
K_{55}	1.03E+06	*(N-m)/deg*	K_{55}	2.85E+08	*(N-m)/deg*	K_{55}	2.86E+08	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	1.37E+06	*(N-m)/deg*	K_{66}	1.37E+06	*(N-m)/deg*

Table F.6: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	3.88E+06	*kg*	M_{11}	3.51E+06	*kg*	M_{11}	7.39E+06	*kg*
M_{22}	3.88E+06	*kg*	M_{22}	3.51E+06	*kg*	M_{22}	7.39E+06	*kg*
M_{33}	3.88E+06	*kg*	M_{33}	9.53E+06	*kg*	M_{33}	1.34E+07	*kg*
I_{44}	1.91E+09	*kg-m^2*	I_{44}	4.25E+08	*kg-m^2*	I_{44}	2.34E+09	*kg-m^2*
I_{55}	1.94E+09	*kg-m^2*	I_{55}	4.25E+08	*kg-m^2*	I_{55}	2.37E+09	*kg-m^2*
I_{66}	7.71E+08	*kg-m^2*	I_{66}	6.03E+08	*kg-m^2*	I_{66}	1.37E+09	*kg-m^2*

Table F.7: System Natural Periods

System Natural Periods		
Surge	42.4	*sec*
Sway	42.4	*sec*
Heave	2.7	*sec*
Roll	2.4	*sec*
Pitch	2.4	*sec*
Yaw	26.3	*sec*

Table F.8: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	0.3	*deg*
Pitch	0.3	*deg*
Yaw	5.3	*deg*

Table F.9: Vessel Motion Statistics during 50-year Environment

Environment & Heading		Offset Mean m	Offset RMS m	Offset Tz sec	Offset Min m	Offset Max m	Heave Mean m	Heave RMS m	Heave Tz sec	Heave Min m	Heave Max m	Heel Mean deg	Heel RMS deg	Heel Tz sec	Heel Min deg	Heel Max deg	Yaw Mean deg	Yaw RMS deg	Yaw Tz sec	Yaw Min deg	Yaw Max deg
50-yr	0°	8.8	4.6	24.5	-7.3	24.9	-0.94	0.30	13.7	-2.1	0.17	0.09	0.08	5.7	-0.23	0.42	0.26	0.38	13.3	-1.1	1.6
	22.5°	8.3	4.3	25.2	-6.8	23.4	-0.92	0.28	13.0	-1.9	0.10	0.11	0.13	7.5	-0.38	0.60	0.82	1.1	13.2	-3.4	5.0
	45°	7.7	4.1	26.1	-6.4	21.8	-0.88	0.25	12.2	-1.8	0.02	0.11	0.13	6.6	-0.39	0.62	0.80	0.50	20.1	-1.0	2.6

Table F.10: Minimum Tendon Tensions during 50-year Environment

Environment & Heading		Minimum Tension Tendon 1 N	Tendon 2 N	Tendon 3 N	Tendon 4 N	Tendon 5 N	Tendon 6 N	Tendon 7 N	Tendon 8 N
50-yr	0°	-1.15E+06	-1.03E+06	-7.97E+04	-3.73E+03	-1.14E+04	-8.93E+04	-1.04E+06	-1.16E+06
	22.5°	-1.42E+06	-1.35E+06	-2.48E+05	-1.11E+05	1.32E+05	8.34E+04	-7.50E+05	-9.10E+05
	45°	-1.57E+06	-1.54E+06	-3.54E+05	-1.83E+05	1.39E+05	1.06E+05	-5.40E+05	-7.14E+05

Table F.11: Maximum Tendon Tensions during 50-year Environment

Environment & Heading		Maximum Tension Tendon 1 N	Tendon 2 N	Tendon 3 N	Tendon 4 N	Tendon 5 N	Tendon 6 N	Tendon 7 N	Tendon 8 N
50-yr	0°	6.91E+06	6.87E+06	6.67E+06	6.68E+06	6.69E+06	6.69E+06	6.88E+06	6.92E+06
	22.5°	7.14E+06	7.15E+06	6.78E+06	6.73E+06	6.52E+06	6.50E+06	6.59E+06	6.67E+06
	45°	7.26E+06	7.29E+06	6.83E+06	6.74E+06	6.48E+06	6.44E+06	6.37E+06	6.46E+06

F.2 Design Iteration #2

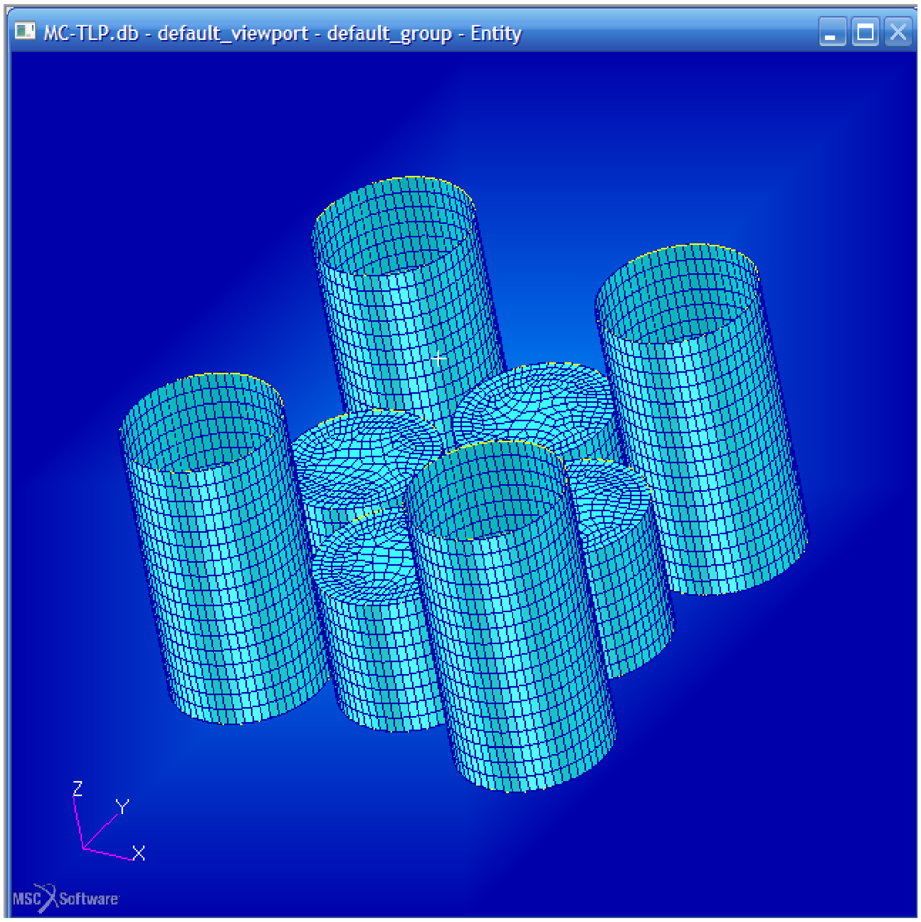


Figure F.3: Patran Model of Vessel

Table F.12: Vessel General Dimensions and Displacement

Parameter			Value			
Pontoon	Pontoon Cell diameter		**10.0**	*m*	32.8	*ft*
	Pontoon Cell height		**1**	*m*	3	*ft*
	Pontoon Cell cross-section		**78.5**	m^2	845	ft^2
	Pontoon Height	***b***	**8.60**	*m*	28	*ft*
	Displaced volume of pontoons		**2,703**	m^3	95,438	ft^3
Column	Column Cell diameter	***a***	**10.0**	*m*	33	*ft*
	Column Cell cross-section		**79**	m^2	845	ft^2
	Column height	***c***	**27.21**	*m*	89	*ft*
	Displaced volume of columns		**5,405**	m^3	190,876	ft^3
	Water plane area		**314**	m^2	3,381	ft^2
Total Displaced Volume			**8,108**	m^3	286,314	ft^3

Draft	***d***	**17**	*m*	56	*ft*
Displacement		81,510	*kN*	**18,324**	*kips*
Distance from Keel to Center of Buoyancy	***KB***	**7.2**	*m*	24	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	**3.9**	*m*	13	*ft*
Distance from Keel to Metacenter	***KM***	**11**	*m*	36	*ft*

Table F.13: Vessel Weight and Force Breakdown Groups

Parameter	Value			
Pontoon Steel	4,245	*kN*	**954**	*kips*
Special Steel	**425**	*kN*	95	*kips*
Pontoon Outfit and Equipment	**637**	*kN*	143	*kips*
Pontoon Subtotal	**5,307**	*kN*	1,193	*kips*
Column Steel	13,425	*kN*	**3,018**	*kips*
Special Steel	**1,343**	*kN*	302	*kips*
Column Outfit and Equipment	**2,014**	*kN*	453	*kips*
Column Subtotal	**16,782**	*kN*	3,773	*kips*
Deck Steel (basic structure)	**1,674**	*kN*	376	*kips*
Deck Steel (deck houses)	**0**	*kN*	0	*kips*
Special Steel	**0**	*kN*	0	*kips*
Rotor	**2,166**	*kN*	487	*kips*
Drivetrain	**2,923**	*kN*	657	*kips*
Add'l Deck Equipment & Outfit - Marine & Support	**0**	*kN*	0	*kips*
Add'l Deck Equipment & Outfit - Mission Systems	**491**	*kN*	110	*kips*
Topsides Subtotal	**7,254**	*kN*	1,631	*kips*
Other Hull Weight	**0**	*kN*	0	*kips*
Deck Reserve/Margin	**167**	*kN*	38	*kips*
Pontoon Fixed Ballast	**0**	*kN*	0	*kips*
LIGHTSHIP	**29,510**	*kN*	6,634	*kips*
Mooring Tension	**32,000**	*kN*	7,194	*kips*
Deck Variable Load	**0**	*kN*	0	*kips*
Column Variable Load	**0**	*kN*	0	*kips*
Water Ballast (pontoon/column)	**20,000**	*kN*	4,496	*kips*
Subtotal External Load, Variable Load, and Ballast	**52,000**	*kN*	11,690	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	**81,510**	*kN*	18,324	*kips*

Distance from Keel to Center of Gravity	***KG***	**8.27**	*m*	27	*ft*
Distance from Center of Gravity to Metacenter	***GM***	**2.76**	*m*	9	*ft*

Table F.14: Vessel Center of Gravity and Moments of Inertia Calculations

						Component Mass and Center of Gravity				Component Moments of Inertia					
Item	Component	X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2
Pontoon	Pontoon 1 (East)	--	--	8.60	676	7.610	0.00	-12.90	135,235	2.42E+07	3.20E+07	9.52E+06	0.00E+00	0.00E+00	1.33E+07
	Pontoon 2 (North)	--	--	8.60	676	0.00	7.610	-12.90	135,235	3.20E+07	2.42E+07	9.52E+06	0.00E+00	1.33E+07	0.00E+00
	Pontoon 3 (West)	--	--	8.60	676	-7.610	0.00	-12.90	135,235	2.42E+07	3.20E+07	9.52E+06	0.00E+00	0.00E+00	-1.33E+07
	Pontoon 4 (South)	--	--	8.60	676	0.00	-7.610	-12.90	135,235	3.20E+07	2.42E+07	9.52E+06	0.00E+00	-1.33E+07	0.00E+00
	Subtotal					0.00	0.00	-12.90	540,940	1.12E+08	1.12E+08	3.81E+07	0.00E+00	0.00E+00	0.00E+00
Column	Column 1 (NE)	--	--	27.21	8,547	10.395	10.395	-3.60	427,672	8.08E+07	8.08E+07	9.78E+07	-4.62E+07	1.60E+07	1.60E+07
	Column 2 (NW)	--	--	27.21	8,547	-10.395	10.395	-3.60	427,672	8.08E+07	8.08E+07	9.78E+07	4.62E+07	1.60E+07	-1.60E+07
	Column 3 (SW)	--	--	27.21	8,547	-10.395	-10.395	-3.60	427,672	8.08E+07	8.08E+07	9.78E+07	-4.62E+07	-1.60E+07	-1.60E+07
	Column 4 (SE)	--	--	27.21	8,547	10.395	-10.395	-3.60	427,672	8.08E+07	8.08E+07	9.78E+07	4.62E+07	-1.60E+07	1.60E+07
	Subtotal					0.00	0.00	-3.60	1,710,687	3.23E+08	3.23E+08	3.91E+08	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	10.00	170,640	2.30E+07	2.30E+07	1.14E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	32.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	32.50	298,000	1.41E+09	1.44E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	32.50	50,000						
	Subtotal					0.00	0.00	27.31	739,440	1.43E+09	1.46E+09	4.62E+07	0.00E+00	0.00E+00	0.00E+00
Pontoon Fixed Ballast	Pontoon 1 (East)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 2 (North)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 3 (West)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 4 (South)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal														
Water Ballast	Pontoon 1 (East)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 2 (North)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 3 (West)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 4 (South)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Column 1 (NE)	--	--	27.21	497	10.395	10.395	-14.04	509,775	1.90E+08	1.90E+08	1.17E+08	-5.51E+07	7.44E+07	7.44E+07
	Column 2 (NW)	--	--	27.21	497	-10.395	10.395	-14.04	509,775	1.90E+08	1.90E+08	1.17E+08	5.51E+07	7.44E+07	-7.44E+07
	Column 3 (SW)	--	--	27.21	497	-10.395	-10.395	-14.04	509,775	1.90E+08	1.90E+08	1.17E+08	-5.51E+07	-7.44E+07	-7.44E+07
	Column 4 (SE)	--	--	27.21	497	10.395	-10.395	-14.04	509,775	1.90E+08	1.90E+08	1.17E+08	5.51E+07	-7.44E+07	7.44E+07
	Subtotal				1,989	0.00	0.00	-14.04	2,039,100	7.61E+08	7.61E+08	4.66E+08	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	10.00	17,064	2.30E+06	2.30E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	10.00	17,064	2.30E+06	2.30E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						0.00	0.00	-4.24	5,047,231	2.63E+09	2.66E+09	9.43E+08	0.00E+00	0.00E+00	0.00E+00

Table F.15: Principal Tendon Details

Tendon	Fairlead Location			Pile Location			Line Length	Line Diameter	MBL	EA
	X	Y	Z	X	Y	Z				
#	m	m	m	m	m	m	m	mm	kN	kN
1	15.5	13.0	-17.2	15.5	13.0	-150.0	132.8	153	22,070	2110
2	13.0	15.5	-17.2	13.0	15.5	-150.0	132.8	153	22,070	2110
3	-13.0	15.5	-17.2	-13.0	15.5	-150.0	132.8	153	22,070	2110
4	-15.5	13.0	-17.2	-15.5	13.0	-150.0	132.8	153	22,070	2110
5	-15.5	-13.0	-17.2	-15.5	-13.0	-150.0	132.8	153	22,070	2110
6	-13.0	-15.5	-17.2	-13.0	-15.5	-150.0	132.8	153	22,070	2110
7	13.0	-15.5	-17.2	13.0	-15.5	-150.0	132.8	153	22,070	2110
8	15.5	-13.0	-17.2	15.5	-13.0	-150.0	132.8	153	22,070	2110

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness

Table F.16: Principal Vessel and Tendon Stiffness Values

Vessel Hydrostatic Stiffness			Tendon System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	2.37E+05	*N/m*	K_{11}	2.37E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	2.37E+05	*N/m*	K_{22}	2.37E+05	*N/m*
K_{33}	3.15E+06	*N/m*	K_{33}	1.27E+08	*N/m*	K_{33}	1.30E+08	*N/m*
K_{44}	-6.29E+06	*(N-m)/deg*	K_{44}	4.63E+08	*(N-m)/deg*	K_{44}	4.57E+08	*(N-m)/deg*
K_{55}	-6.29E+06	*(N-m)/deg*	K_{55}	4.63E+08	*(N-m)/deg*	K_{55}	4.57E+08	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	1.69E+06	*(N-m)/deg*	K_{66}	1.69E+06	*(N-m)/deg*

Table F.17: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	5.05E+06	*kg*	M_{11}	5.68E+06	*kg*	M_{11}	1.07E+07	*kg*
M_{22}	5.05E+06	*kg*	M_{22}	5.68E+06	*kg*	M_{22}	1.07E+07	*kg*
M_{33}	5.05E+06	*kg*	M_{33}	5.37E+06	*kg*	M_{33}	1.04E+07	*kg*
I_{44}	2.63E+09	*kg-m*^{2}	I_{44}	6.33E+08	*kg-m*^{2}	I_{44}	3.26E+09	*kg-m*^{2}
I_{55}	2.66E+09	*kg-m*^{2}	I_{55}	6.33E+08	*kg-m*^{2}	I_{55}	3.30E+09	*kg-m*^{2}
I_{66}	1.69E+06	*kg-m*^{2}	I_{66}	7.79E+08	*kg-m*^{2}	I_{66}	7.81E+08	*kg-m*^{2}

Table F.18: System Natural Periods

System Natural Periods		
Surge	42.3	*sec*
Sway	42.3	*sec*
Heave	1.8	*sec*
Pitch	2.2	*sec*
Roll	2.2	*sec*
Yaw	26.5	*sec*

Table F.19: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	0.2	*deg*
Pitch	0.2	*deg*
Yaw	4.3	*deg*

Table F.20: Vessel Motion Statistics during 50-year Environment and Maximum Operating Load Cases

Environment & Heading		Offset Mean m	Offset RMS m	Offset Tz sec	Offset Min m	Offset Max m	Heave Mean m	Heave RMS m	Heave Tz sec	Heave Min m	Heave Max m	Heel Mean deg	Heel RMS deg	Heel Tz sec	Heel Min deg	Heel Max deg	Yaw Mean deg	Yaw RMS deg	Yaw Tz sec	Yaw Min deg	Yaw Max deg
50-yr	0°	5.3	2.6	18.8	-3.9	14.5	-0.11	0.11	15.2	-0.5	0.28	0.08	0.04	3.3	-0.06	0.22	0.00	0.00	33.9	0.0	0.0
	22.5°	4.9	2.2	17.4	-3.0	12.8	-0.09	0.08	13.1	-0.4	0.22	0.08	0.07	10.9	-0.16	0.33	0.42	1.50	23.1	-4.9	5.7
	45°	4.3	1.8	15.9	-2.3	10.9	-0.07	0.06	10.7	-0.3	0.16	0.07	0.04	4.6	-0.07	0.21	-0.07	0.26	22.0	-1.0	0.8
Max Oper	0°	5.3	2.6	18.8	-3.9	14.5	-0.10	0.02	17.8	-0.16	-0.04	0.24	0.24	4.70	-0.72	1.19	-5.36	0.12	6.15	-5.82	-4.90
	22.5°	4.9	2.2	17.4	-3.0	12.8	-0.20	0.02	21.6	-0.28	-0.12	0.35	0.25	4.95	-0.62	1.31	-6.90	0.17	7.40	-7.57	-6.24
	45°	4.3	1.8	15.9	-2.3	10.9	-0.20	0.02	21.5	-0.28	-0.12	0.35	0.25	4.89	-0.62	1.31	-6.92	0.16	7.45	-7.54	-6.29

Table F.21: Minimum Tendon Tensions during 50-year Environment and Maximum Operating Load Cases

Environment & Heading		Minimum Tension							
		Tendon 1 N	Tendon 2 N	Tendon 3 N	Tendon 4 N	Tendon 5 N	Tendon 6 N	Tendon 7 N	Tendon 8 N
50-yr	0°	1.04E+06	1.14E+06	1.76E+06	1.78E+06	1.78E+06	1.76E+06	1.14E+06	1.04E+06
	22.5°	9.89E+05	1.05E+06	1.78E+06	1.83E+06	1.86E+06	1.83E+06	1.31E+06	1.22E+06
	45°	9.50E+05	9.94E+05	1.73E+06	1.80E+06	1.82E+06	1.78E+06	1.37E+06	1.29E+06
Max Oper	0°	9.00E+05	8.20E+05	1.30E+06	1.53E+06	1.84E+06	1.52E+06	-5.62E+03	7.43E+04
	22.5°	2.97E+05	3.03E+05	2.21E+05	3.76E+05	1.68E+06	1.52E+06	-6.08E+05	-6.81E+05
	45°	6.20E+03	1.78E+05	2.62E+04	8.21E+04	1.60E+06	1.70E+06	-2.09E+05	-4.28E+05

Table F.22: Maximum Tendon Tensions during 50-year Environment and Maximum Operating Load Cases

Environment & Heading		Maximum Tension							
		Tendon 1 N	Tendon 2 N	Tendon 3 N	Tendon 4 N	Tendon 5 N	Tendon 6 N	Tendon 7 N	Tendon 8 N
50-yr	0°	4.24E+06	4.25E+06	4.83E+06	4.93E+06	4.93E+06	4.83E+06	4.25E+06	4.24E+06
	22.5°	4.26E+06	4.30E+06	4.72E+06	4.78E+06	4.85E+06	4.78E+06	4.16E+06	4.12E+06
	45°	4.30E+06	4.34E+06	4.65E+06	4.70E+06	4.86E+06	4.81E+06	4.17E+06	4.14E+06
Max Oper	0°	4.14E+06	4.47E+06	6.00E+06	5.93E+06	5.09E+06	5.17E+06	4.67E+06	4.44E+06
	22.5°	2.98E+06	3.14E+06	5.29E+06	5.37E+06	4.40E+06	4.38E+06	4.44E+06	4.28E+06
	45°	3.05E+06	2.95E+06	4.89E+06	5.11E+06	4.69E+06	4.52E+06	4.64E+06	4.58E+06

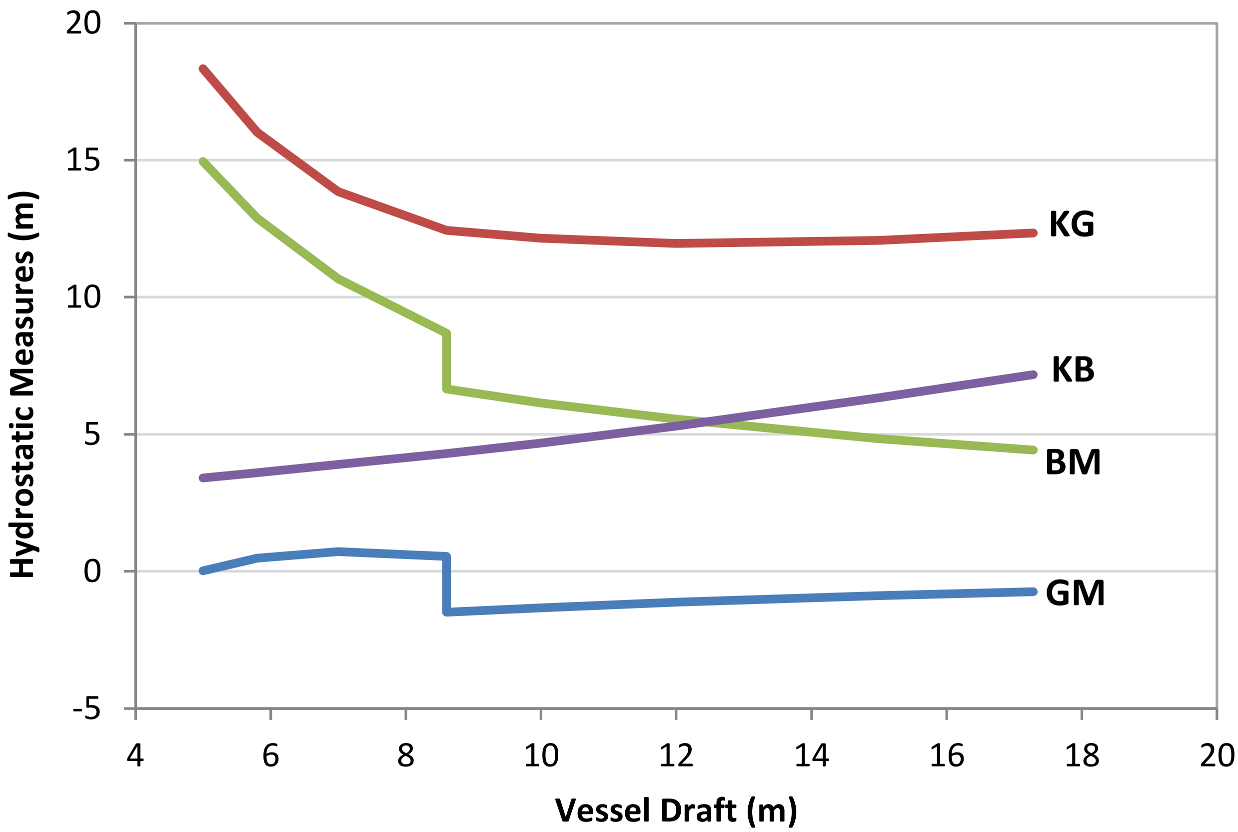


Figure F.4: Hydrostatic Measure vs. Vessel Draft

F.3 Design Iteration #3

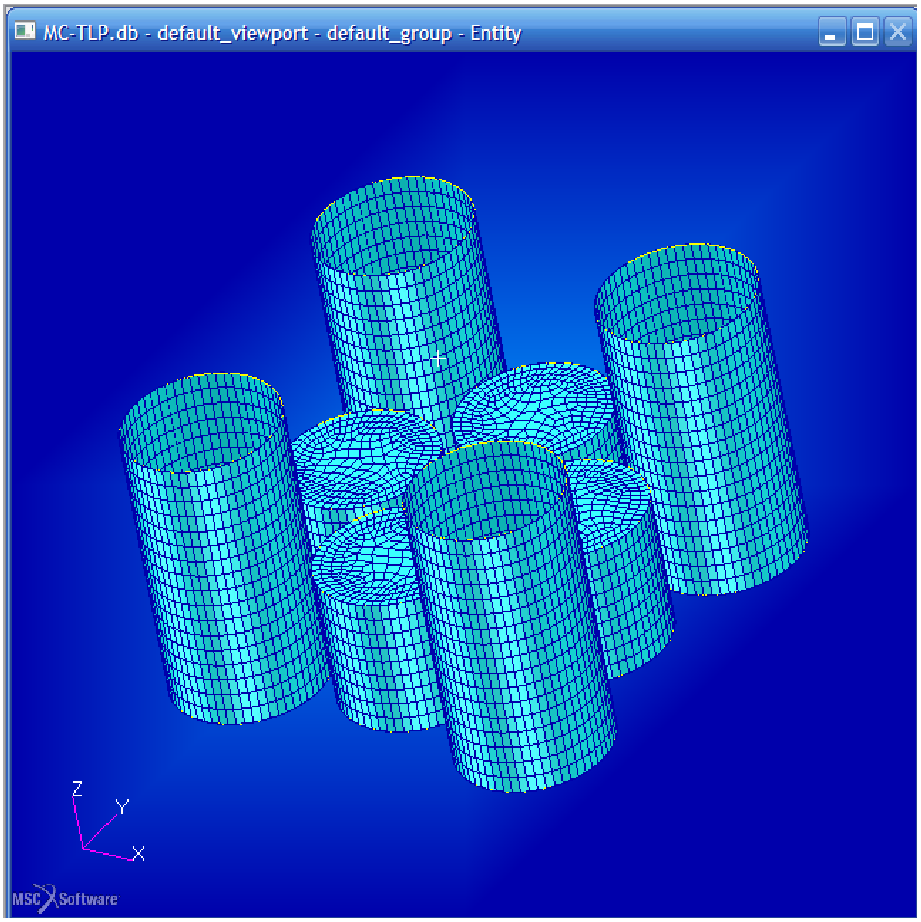


Figure F.5: Patran Model of Vessel

Table F.23: Vessel General Dimensions and Displacement

Parameter			Value			
Pontoon	Pontoon Cell diameter		11.0	*m*	36	*ft*
	Pontoon Cell cross-section		95.0	m^2	1,023	ft^2
	Pontoon Height	***b***	8.60	*m*	28	*ft*
	Displaced volume of pontoons		3,270	m^3	115,480	ft^3
Column	Column Cell diameter	***a***	11.0	*m*	36	*ft*
	Column Cell cross-section		95	m^2	1,023	ft^2
	Column height	***c***	27.2	*m*	89	*ft*
	Displaced volume of columns		6,540	m^3	230,960	ft^3
	Water plane area		380	m^2	4,092	ft^2
TOTAL DISPLACED VOLUME			9,810	m^3	346,440	ft^3

Draft	***d***	17.2	*m*	56	*ft*
Displacement		98,627	*kN*	22,172	*kips*
Distance from Keel to Center of Buoyancy	***KB***	7.2	*m*	24	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	5.3	*m*	17	*ft*
Distance from Keel to Metacenter	***KM***	12	*m*	41	*ft*

Table F.24: Vessel Weight and Force Breakdown Groups

Parameter	Value			
Pontoon Steel	5,137	*kN*	1,155	*kips*
Special Steel	514	*kN*	115	*kips*
Pontoon Outfit and Equipment	771	*kN*	173	*kips*
Pontoon Subtotal	6,421	*kN*	1,444	*kips*
Column Steel	16,245	*kN*	3,652	*kips*
Special Steel	1,624	*kN*	365	*kips*
Column Outfit and Equipment	2,437	*kN*	548	*kips*
Column Subtotal	20,306	*kN*	4,565	*kips*
Deck Steel (basic structure)	1,674	*kN*	376	*kips*
Deck Steel (deck houses)	0	*kN*	0	*kips*
Special Steel	0	*kN*	0	*kips*
Rotor	2,166	*kN*	487	*kips*
Drivetrain	2,923	*kN*	657	*kips*
Add'l Deck Equipment & Outfit - Marine & Support	0	*kN*	0	*kips*
Add'l Deck Equipment & Outfit - Mission Systems	491	*kN*	110	*kips*
Topsides Subtotal	7,254	*kN*	1,631	*kips*
Other Hull Weight	0	*kN*	0	*kips*
Deck Reserve/Margin	167	*kN*	38	*kips*
Pontoon Fixed Ballast	0	*kN*	0	*kips*
LIGHTSHIP	34,148	*kN*	7,677	*kips*
Mooring Tension	24,000	*kN*	5,395	*kips*
Deck Variable Load	0	*kN*	0	*kips*
Column Variable Load	0	*kN*	0	*kips*
Water Ballast (pontoon/column)	40,478	*kN*	9,100	*kips*
Subtotal External Load, Variable Load, and Ballast	64,478	*kN*	14,495	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE	98,627	*kN*	22,172	*kips*

Distance from Keel to Center of Gravity	***KG***	8.8	*m*	29	*ft*
Distance from Center of Gravity to Metacenter	***GM***	3.6	*m*	12	*ft*

Table F.25: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component Mass and Center of Gravity				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2	kg-m^2
Pontoon	Pontoon 1 (East)	--	--	8.60	818	8.32	0.00	-12.90	163,634	2.95E+07	4.08E+07	1.38E+07	0.00E+00	0.00E+00	1.76E+07
	Pontoon 2 (North)	--	--	8.60	818	0.00	8.32	-12.90	163,634	4.08E+07	2.95E+07	1.38E+07	0.00E+00	1.76E+07	0.00E+00
	Pontoon 3 (West)	--	--	8.60	818	-8.32	0.00	-12.90	163,634	2.95E+07	4.08E+07	1.38E+07	0.00E+00	0.00E+00	-1.76E+07
	Pontoon 4 (South)	--	--	8.60	818	0.00	-8.32	-12.90	163,634	4.08E+07	2.95E+07	1.38E+07	0.00E+00	-1.76E+07	0.00E+00
	Subtotal					0.00	0.00	-12.90	654,538	1.41E+08	1.41E+08	5.52E+07	0.00E+00	0.00E+00	0.00E+00
Column	Column 1 (NE)	--	--	27.21	10,342	11.36	11.36	-3.60	517,483	1.09E+08	1.09E+08	1.41E+08	-6.68E+07	2.12E+07	2.12E+07
	Column 2 (NW)	--	--	27.21	10,342	-11.36	11.36	-3.60	517,483	1.09E+08	1.09E+08	1.41E+08	6.68E+07	2.12E+07	-2.12E+07
	Column 3 (SW)	--	--	27.21	10,342	-11.36	-11.36	-3.60	517,483	1.09E+08	1.09E+08	1.41E+08	-6.68E+07	-2.12E+07	-2.12E+07
	Column 4 (SE)	--	--	27.21	10,342	11.36	-11.36	-3.60	517,483	1.09E+08	1.09E+08	1.41E+08	6.68E+07	-2.12E+07	2.12E+07
	Subtotal					0.00	0.00	-3.60	2,069,931	4.37E+08	4.37E+08	5.66E+08	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	10.00	170,640	2.30E+07	2.30E+07	1.14E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	32.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	32.50	298,000	1.41E+09	1.44E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	32.50	50,000						
	Subtotal					0.00	0.00	27.31	739,440	1.43E+09	1.46E+09	4.62E+07	0.00E+00	0.00E+00	0.00E+00
Pontoon Fixed Ballast	Pontoon 1 (East)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 2 (North)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 3 (West)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 4 (South)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					--	--	--	--	--	--	--	--	--	--
Water Ballast	Pontoon 1 (East)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 2 (North)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 3 (West)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Pontoon 4 (South)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Column 1 (NE)	--	--	27.21	1,006	11.36	11.36	-11.91	1,031,746	3.51E+08	3.51E+08	2.82E+08	-1.33E+08	1.40E+08	1.40E+08
	Column 2 (NW)	--	--	27.21	1,006	-11.36	11.36	-11.91	1,031,746	3.51E+08	3.51E+08	2.82E+08	1.33E+08	1.40E+08	-1.40E+08
	Column 3 (SW)	--	--	27.21	1,006	-11.36	-11.36	-11.91	1,031,746	3.51E+08	3.51E+08	2.82E+08	-1.33E+08	-1.40E+08	-1.40E+08
	Column 4 (SE)	--	--	27.21	1,006	11.36	-11.36	-11.91	1,031,746	3.51E+08	3.51E+08	2.82E+08	1.33E+08	-1.40E+08	1.40E+08
	Subtotal				4,026	0.00	0.00	-11.91	4,126,982	1.40E+09	1.40E+09	1.13E+09	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	10.00	17,064	2.30E+06	2.30E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	10.00	17,064	2.30E+06	2.30E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						**0.00**	**0.00**	**-5.87**	**7,607,955**	**3.42E+09**	**3.45E+09**	**1.80E+09**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table F.26: Principal Tendon Details

Tendon	Fairlead Location			Pile Location			Line Length	Line Diameter	MBL	EA
	X	Y	Z	X	Y	Z				
#	m	m	m	m	m	m	m	mm	kN	kN
1	17.5	13.0	-17.2	17.5	13.0	-150.0	132.8	153	22,070	2110
2	13.0	17.5	-17.2	13.0	17.5	-150.0	132.8	153	22,070	2110
3	-13.0	17.5	-17.2	-13.0	17.5	-150.0	132.8	153	22,070	2110
4	-17.5	13.0	-17.2	-17.5	13.0	-150.0	132.8	153	22,070	2110
5	-17.5	-13.0	-17.2	-17.5	-13.0	-150.0	132.8	153	22,070	2110
6	-13.0	-17.5	-17.2	-13.0	-17.5	-150.0	132.8	153	22,070	2110
7	13.0	-17.5	-17.2	13.0	-17.5	-150.0	132.8	153	22,070	2110
8	17.5	-13.0	-17.2	17.5	-13.0	-150.0	132.8	153	22,070	2110

Notes: MBL ≡ Minimum Breaking Load
EA ≡ Axial Stiffness

Table F.27: Principal Vessel and Tendon Stiffness Values

Vessel Hydrostatic Stiffness			Tendon System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	1.77E+05	*N/m*	K_{11}	1.77E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	1.77E+05	*N/m*	K_{22}	1.77E+05	*N/m*
K_{33}	3.82E+06	*N/m*	K_{33}	1.27E+08	*N/m*	K_{33}	1.30E+08	*N/m*
K_{44}	-4.00E+06	*(N-m)/deg*	K_{44}	5.33E+08	*(N-m)/deg*	K_{44}	5.29E+08	*(N-m)/deg*
K_{55}	-4.00E+06	*(N-m)/deg*	K_{55}	5.33E+08	*(N-m)/deg*	K_{55}	5.29E+08	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	1.47E+06	*(N-m)/deg*	K_{66}	1.47E+06	*(N-m)/deg*

Table F.28: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	7.61E+06	*kg*	M_{11}	6.69E+06	*kg*	M_{11}	1.43E+07	*kg*
M_{22}	7.61E+06	*kg*	M_{22}	6.69E+06	*kg*	M_{22}	1.43E+07	*kg*
M_{33}	7.61E+06	*kg*	M_{33}	7.12E+06	*kg*	M_{33}	1.47E+07	*kg*
I_{44}	3.42E+09	*kg-m²*	I_{44}	8.00E+08	$kg\text{-}m^2$	I_{44}	4.22E+09	$kg\text{-}m^2$
I_{55}	3.45E+09	$kg\text{-}m^2$	I_{55}	8.00E+08	$kg\text{-}m^2$	I_{55}	4.25E+09	$kg\text{-}m^2$
I_{66}	1.80E+09	$kg\text{-}m^2$	I_{66}	1.11E+09	$kg\text{-}m^2$	I_{66}	2.91E+09	$kg\text{-}m^2$

Table F.29: System Natural Periods

System Natural Periods		
Surge	56.5	*sec*
Sway	56.5	*sec*
Heave	2.1	*sec*
Pitch	2.3	*sec*
Roll	2.4	*sec*
Yaw	36.9	*sec*

Table F.30: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	0.1	*deg*
Pitch	0.1	*deg*
Yaw	5.0	*deg*

Table F.31: Vessel Motion Statistics during 50-year Environment and Maximum Operating Load Cases

Environment & Heading		Offset Mean m	Offset RMS m	Offset Tz sec	Offset Min m	Offset Max m	Heave Mean m	Heave RMS m	Heave Tz sec	Heave Min m	Heave Max m	Heel Mean deg	Heel RMS deg	Heel Tz sec	Heel Min deg	Heel Max deg	Yaw Mean deg	Yaw RMS deg	Yaw Tz sec	Yaw Min deg	Yaw Max deg
50-yr	0°	5.8	3.3	25.1	-5.9	17.4	-0.12	0.15	18.4	-0.65	0.40	0.07	0.03	3.9	-0.05	0.20	0.00	0.00	37.0	0.00	0.00
	22.5°	5.2	2.8	22.9	-4.5	15.0	-0.10	0.11	15.5	-0.52	0.31	0.07	0.08	7.7	-0.25	0.39	0.55	1.83	27.8	-5.75	6.86
	45°	4.6	2.2	20.2	-3.2	12.4	-0.08	0.08	12.4	-0.39	0.23	0.06	0.03	4.5	-0.07	0.19	0.07	0.07	46.3	-0.16	0.30
Max Oper	0°	6.0	0.6	40.0	4.2	7.9	-0.20	0.02	21.7	-0.28	-0.11	0.29	0.21	4.7	-0.55	1.12	-5.85	0.16	10.5	-6.5	-5.2
	22.5°	6.0	0.6	42.2	4.2	7.9	-0.19	0.02	21.3	-0.28	-0.11	0.29	0.21	4.9	-0.55	1.12	-5.85	0.17	9.8	-6.5	-5.2
	45°	6.0	0.5	44.6	4.2	7.8	-0.19	0.02	21.3	-0.28	-0.11	0.29	0.21	4.9	-0.55	1.12	-5.85	0.16	10.3	-6.4	-5.3

Table F.32: Minimum Tendon Tensions during 50-year Environment and Maximum Operating Load Cases

Environment & Heading		Minimum Tension Tendon 1 N	Tendon 2 N	Tendon 3 N	Tendon 4 N	Tendon 5 N	Tendon 6 N	Tendon 7 N	Tendon 8 N
50-yr	0°	6.29E+05	7.67E+05	1.31E+06	1.35E+06	1.35E+06	1.31E+06	7.67E+05	6.29E+05
	22.5°	4.83E+05	5.69E+05	1.18E+06	1.27E+06	1.40E+06	1.39E+06	9.85E+05	8.12E+05
	45°	5.02E+05	5.21E+05	1.10E+06	1.24E+06	1.46E+06	1.45E+06	1.15E+06	1.00E+06
Max Oper	0°	4.18E+05	2.92E+05	6.80E+05	1.02E+06	1.34E+06	8.46E+05	-4.61E+05	-3.33E+05
	22.5°	4.47E+05	4.54E+05	3.37E+05	5.73E+05	1.73E+06	1.48E+06	-3.65E+05	-4.69E+05
	45°	1.37E+05	3.99E+05	1.93E+05	2.77E+05	1.59E+06	1.74E+06	3.82E+04	-2.93E+05

Table F.33: Maximum Tendon Tensions during 50-year Environment and Maximum Operating Load Cases

Environment & Heading		Maximum Tension Tendon 1 N	Tendon 2 N	Tendon 3 N	Tendon 4 N	Tendon 5 N	Tendon 6 N	Tendon 7 N	Tendon 8 N
50-yr	0°	4.72E+06	4.75E+06	5.23E+06	5.36E+06	5.36E+06	5.23E+06	4.75E+06	4.72E+06
	22.5°	4.78E+06	4.80E+06	5.10E+06	5.21E+06	5.35E+06	5.25E+06	4.75E+06	4.72E+06
	45°	4.79E+06	4.80E+06	4.88E+06	4.95E+06	5.22E+06	5.19E+06	4.83E+06	4.78E+06
Max Oper	0°	3.35E+06	3.85E+06	5.18E+06	5.06E+06	4.29E+06	4.41E+06	4.00E+06	3.65E+06
	22.5°	2.95E+06	3.20E+06	5.08E+06	5.19E+06	4.27E+06	4.26E+06	4.35E+06	4.10E+06
	45°	3.08E+06	2.93E+06	4.67E+06	5.00E+06	4.59E+06	4.32E+06	4.50E+06	4.41E+06

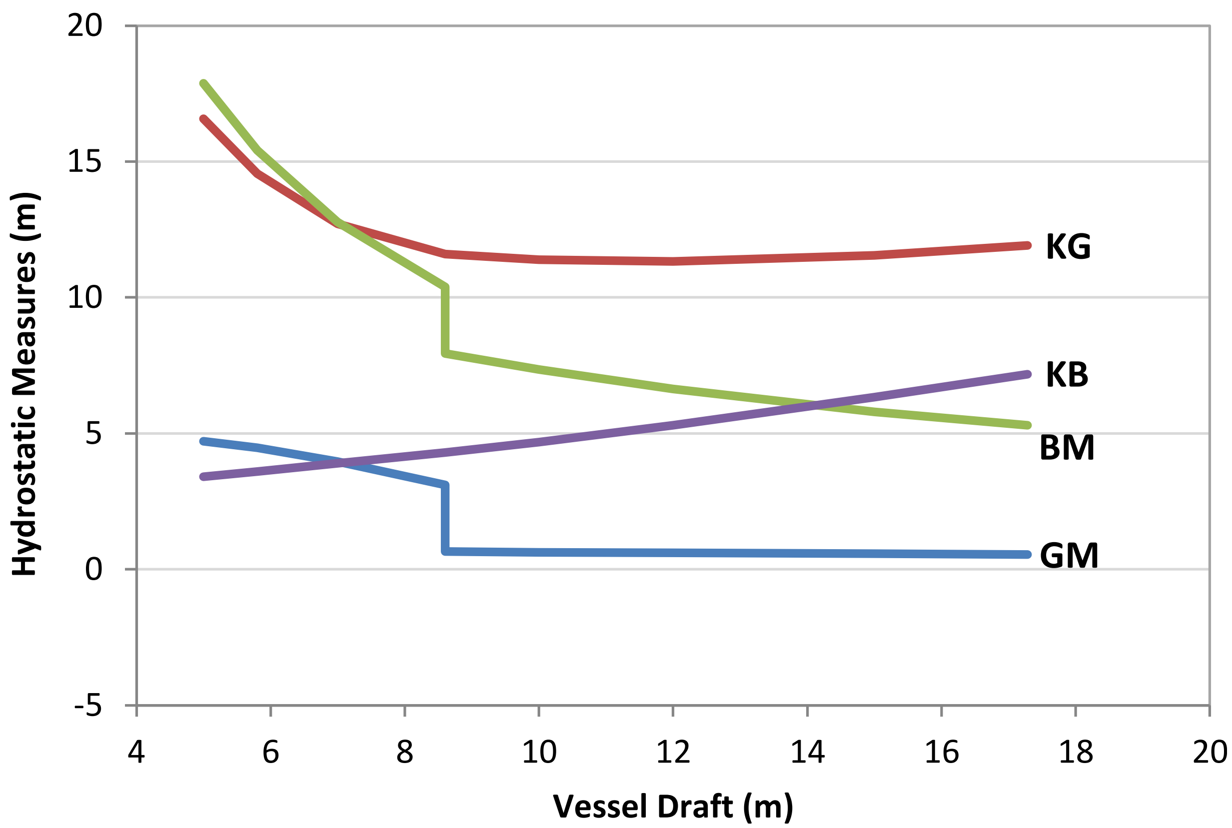


Figure F.6: Hydrostatic Measure vs. Vessel Draft

F.4 Design Iteration #4

Table F.34: Vessel General Dimensions and Displacement

Parameter			Value			
Pontoon	Pontoon Cell diameter		11.0	*m*	36	*ft*
	Pontoon Cell cross-section		95.0	m^2	1,023	ft^2
	Pontoon Height	***b***	8.60	*m*	28	*ft*
	Displaced volume of pontoons		3,270	m^3	115,480	ft^3
Column	Column Cell diameter	***a***	11.0	*m*	36	*ft*
	Column Cell cross-section		95	m^2	1,023	ft^2
	Column height	***c***	27.2	*m*	89	*ft*
	Displaced volume of columns		6,540	m^3	230,960	ft^3
	Water plane area		380	m^2	4,092	ft^2
TOTAL DISPLACED VOLUME			9,810	m^3	346,440	ft^3

Draft	***d***	17.2	*m*	56	*ft*
Displacement		98,627	*kN*	22,172	*kips*
Distance from Keel to Center of Buoyancy	***KB***	7.2	*m*	24	*ft*
Distance from Center of Buoyancy to Metacenter	***BM***	5.3	*m*	17	*ft*
Distance from Keel to Metacenter	***KM***	12	*m*	41	*ft*

Table F.35: Vessel Weight and Force Breakdown Groups

Parameter		Value			
Pontoon Steel		5,137	*kN*	1,155	*kips*
Special Steel		514	*kN*	115	*kips*
Pontoon Outfit and Equipment		771	*kN*	173	*kips*
Pontoon Subtotal		6,421	*kN*	1,444	*kips*
Column Steel		16,245	*kN*	3,652	*kips*
Special Steel		1,624	*kN*	365	*kips*
Column Outfit and Equipment		2,437	*kN*	548	*kips*
Column Subtotal		20,306	*kN*	4,565	*kips*
Deck Steel (basic structure)		1,674	*kN*	376	*kips*
Deck Steel (deck houses)		0	*kN*	0	*kips*
Special Steel		0	*kN*	0	*kips*
Rotor		2,166	*kN*	487	*kips*
Drivetrain		2,923	*kN*	657	*kips*
Add'l Deck Equipment & Outfit - Marine & Support		0	*kN*	0	*kips*
Add'l Deck Equipment & Outfit - Mission Systems		491	*kN*	110	*kips*
Topsides Subtotal		7,254	*kN*	1,631	*kips*
Other Hull Weight		0	*kN*	0	*kips*
Deck Reserve/Margin		167	*kN*	38	*kips*
Pontoon Fixed Ballast		0	*kN*	0	*kips*
LIGHTSHIP		34,148	*kN*	7,677	*kips*
Mooring Tension		28,000	*kN*	6,295	*kips*
Deck Variable Load		0	*kN*	0	*kips*
Column Variable Load		0	*kN*	0	*kips*
Water Ballast (pontoon/column)		36,478	*kN*	8,201	*kips*
Subtotal External Load, Variable Load, and Ballast		64,478	*kN*	14,495	*kips*
TOTAL SUPPORTED WEIGHT AND EXTERNAL FORCE		98,627	*kN*	22,172	*kips*
Distance from Keel to Center of Gravity	***KG***	8.4	*m*	28	*ft*
Distance from Center of Gravity to Metacenter	***GM***	4.0	*m*	13	*ft*

Table F.36: Vessel Center of Gravity and Moments of Inertia Calculations

Item	Component	Component Size and Volume				Component CG and Mass				Component Moments of Inertia					
		X Dim	Y Dim	Z Dim	Volume	X_{CG}	Y_{CG}	Z_{CG}	Mass	I_{XX}	I_{YY}	I_{ZZ}	I_{XY}	I_{YZ}	I_{ZX}
		m	m	m	m^3	m	m	m	kg	$kg\text{-}m^2$	$kg\text{-}m^2$	$kg\text{-}m^2$	$kg\text{-}m^2$	$kg\text{-}m^2$	$kg\text{-}m^2$
Pontoon	Pontoon 1 (East)	--	--	8.60	818	8.32	0.00	-12.90	163,634	2.95E+07	4.08E+07	1.38E+07	0.00E+00	0.00E+00	1.76E+07
	Pontoon 2 (North)	--	--	8.60	818	0.00	8.32	-12.90	163,634	4.08E+07	2.95E+07	1.38E+07	0.00E+00	1.76E+07	0.00E+00
	Pontoon 3 (West)	--	--	8.60	818	-8.32	0.00	-12.90	163,634	2.95E+07	4.08E+07	1.38E+07	0.00E+00	0.00E+00	-1.76E+07
	Pontoon 4 (South)	--	--	8.60	818	0.00	-8.32	-12.90	163,634	4.08E+07	2.95E+07	1.38E+07	0.00E+00	-1.76E+07	0.00E+00
	Subtotal					0.00	0.00	-12.90	654,538	1.41E+08	1.41E+08	5.52E+07	0.00E+00	0.00E+00	0.00E+00
Column	Column 1 (NE)	--	--	27.21	10,342	11.36	11.36	-3.60	517,483	1.09E+08	1.09E+08	1.41E+08	-6.68E+07	2.12E+07	2.12E+07
	Column 2 (NW)	--	--	27.21	10,342	-11.36	11.36	-3.60	517,483	1.09E+08	1.09E+08	1.41E+08	6.68E+07	2.12E+07	-2.12E+07
	Column 3 (SW)	--	--	27.21	10,342	-11.36	-11.36	-3.60	517,483	1.09E+08	1.09E+08	1.41E+08	-6.68E+07	-2.12E+07	-2.12E+07
	Column 4 (SE)	--	--	27.21	10,342	11.36	-11.36	-3.60	517,483	1.09E+08	1.09E+08	1.41E+08	6.68E+07	-2.12E+07	2.12E+07
	Subtotal					0.00	0.00	-3.60	2,069,931	4.37E+08	4.37E+08	5.66E+08	0.00E+00	0.00E+00	0.00E+00
Topsides	Deck Steel (basic structure)	20.00	20.00	4.00	1,600	0.00	0.00	10.00	170,640	2.30E+07	2.30E+07	1.14E+07	0.00E+00	0.00E+00	0.00E+00
	Deck Steel (deck houses)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Special Steel	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Rotor	--	--	--	--	0.00	0.00	32.50	220,800						
	Drivetrain	--	--	--	--	0.00	0.00	32.50	298,000	1.41E+09	1.44E+09	3.48E+07	0.00E+00	0.00E+00	0.00E+00
	Additional Deck Equipment	--	--	--	--	0.00	0.00	32.50	50,000						
	Subtotal					0.00	0.00	27.31	739,440	1.43E+09	1.46E+09	4.62E+07	0.00E+00	0.00E+00	0.00E+00
Pontoon Fixed Ballast	Side 1 (East)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Side 2 (North)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Side 3 (West)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Side 4 (South)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal														
Water Ballast	Side 1 (East)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Side 2 (North)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Side 3 (West)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Side 4 (South)	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Column 1 (NE)	--	--	27.21	907	11.36	11.36	-12.43	929,791	3.28E+08	3.28E+08	2.54E+08	-1.20E+08	1.31E+08	1.31E+08
	Column 2 (NW)	--	--	27.21	907	-11.36	11.36	-12.43	929,791	3.28E+08	3.28E+08	2.54E+08	1.20E+08	1.31E+08	-1.31E+08
	Column 3 (SW)	--	--	27.21	907	-11.36	-11.36	-12.43	929,791	3.28E+08	3.28E+08	2.54E+08	-1.20E+08	-1.31E+08	-1.31E+08
	Column 4 (SE)	--	--	27.21	907	11.36	-11.36	-12.43	929,791	3.28E+08	3.28E+08	2.54E+08	1.20E+08	-1.31E+08	1.31E+08
	Subtotal				3,628	0.00	0.00	-12.43	3,719,162	1.31E+09	1.31E+09	1.02E+09	0.00E+00	0.00E+00	0.00E+00
Deck Margin & Mooring	Deck Reserve/Margin	20.00	20.00	4.00	1,600	0.00	0.00	10.00	17,064	2.30E+06	2.30E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
	Mooring Line Onboard	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Subtotal					0.00	0.00	10.00	17,064	2.30E+06	2.30E+06	1.14E+06	0.00E+00	0.00E+00	0.00E+00
TOTAL						**0.00**	**0.00**	**-5.80**	**7,200,135**	**3.32E+09**	**3.36E+09**	**1.68E+09**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table F.37: Principal Tendon Details

Tendon	Fairlead Location			Pile Location			Line Length	Line Diameter	MBL	EA
	X	Y	Z	X	Y	Z				
#	m	m	m	m	m	m	m	mm	kN	kN
1	17.5	13.0	-17.2	17.5	13.0	-150.0	132.8	153	22,070	2110
2	13.0	17.5	-17.2	13.0	17.5	-150.0	132.8	153	22,070	2110
3	-13.0	17.5	-17.2	-13.0	17.5	-150.0	132.8	153	22,070	2110
4	-17.5	13.0	-17.2	-17.5	13.0	-150.0	132.8	153	22,070	2110
5	-17.5	-13.0	-17.2	-17.5	-13.0	-150.0	132.8	153	22,070	2110
6	-13.0	-17.5	-17.2	-13.0	-17.5	-150.0	132.8	153	22,070	2110
7	13.0	-17.5	-17.2	13.0	-17.5	-150.0	132.8	153	22,070	2110
8	17.5	-13.0	-17.2	17.5	-13.0	-150.0	132.8	153	22,070	2110

Notes: MBL ≡ Minimum Breaking Load

EA ≡ Axial Stiffness

Table F.38: Principal Vessel and Tendon Stiffness Values

Vessel Hydrostatic Stiffness			Mooring System Stiffness			Total System Stiffness		
K_{11}	0.00E+00	*N/m*	K_{11}	2.07E+05	*N/m*	K_{11}	2.07E+05	*N/m*
K_{22}	0.00E+00	*N/m*	K_{22}	2.07E+05	*N/m*	K_{22}	2.07E+05	*N/m*
K_{33}	3.82E+06	*N/m*	K_{33}	1.27E+08	*N/m*	K_{33}	1.31E+08	*N/m*
K_{44}	-4.00E+06	*(N-m)/deg*	K_{44}	5.35E+08	*(N-m)/deg*	K_{44}	5.31E+08	*(N-m)/deg*
K_{55}	-4.00E+06	*(N-m)/deg*	K_{55}	5.35E+08	*(N-m)/deg*	K_{55}	5.31E+08	*(N-m)/deg*
K_{66}	0.00E+00	*(N-m)/deg*	K_{66}	1.72E+06	*(N-m)/deg*	K_{66}	1.72E+06	*(N-m)/deg*

Table F.39: Principal Vessel Mass and Inertia Values

Vessel Mass/Inertia			Vessel Added Mass/Inertia			Total System Mass/Inertia		
M_{11}	7.20E+06	*kg*	M_{11}	6.69E+06	*kg*	M_{11}	1.39E+07	*kg*
M_{22}	7.20E+06	*kg*	M_{22}	6.69E+06	*kg*	M_{22}	1.39E+07	*kg*
M_{33}	7.20E+06	*kg*	M_{33}	7.12E+06	*kg*	M_{33}	1.43E+07	*kg*
I_{44}	3.32E+09	*kg-m²*	I_{44}	8.00E+08	$kg\text{-}m^2$	I_{44}	4.12E+09	$kg\text{-}m^2$
I_{55}	3.36E+09	$kg\text{-}m^2$	I_{55}	8.00E+08	$kg\text{-}m^2$	I_{55}	4.16E+09	$kg\text{-}m^2$
I_{66}	1.68E+09	$kg\text{-}m^2$	I_{66}	1.11E+09	$kg\text{-}m^2$	I_{66}	2.79E+09	$kg\text{-}m^2$

Table F.40: System Natural Periods

System Natural Periods		
Surge	51.5	*sec*
Sway	51.5	*sec*
Heave	2.1	*sec*
Pitch	2.3	*sec*
Roll	2.3	*sec*
Yaw	33.5	*sec*

Table F.41: Estimated Maximum Vessel Rotations

Estimated Maximum Rotations		
Roll	0.1	*deg*
Pitch	0.1	*deg*
Yaw	4.2	*deg*

Table F.42: Vessel Motion Statistics during 50-year Environment and Maximum Operating Load Cases

Environment & Heading		Offset Mean m	Offset RMS m	Offset Tz sec	Offset Min m	Offset Max m	Heave Mean m	Heave RMS m	Heave Tz sec	Heave Min m	Heave Max m	Heel Mean deg	Heel RMS deg	Heel Tz sec	Heel Min deg	Heel Max deg	Yaw Mean deg	Yaw RMS deg	Yaw Tz sec	Yaw Min deg	Yaw Max deg
50-yr	0°	5.0	3.2	23.1	-6.1	16.1	-0.09	0.12	16.5	-0.5	0.35	0.07	0.03	4.5	-0.05	0.19	0.00	0.00	33.8	0.0	0.0
	22.5°	4.5	2.6	21.1	-4.8	13.9	-0.08	0.10	13.9	-0.4	0.27	0.07	0.07	6.0	-0.20	0.34	0.47	1.7	25.1	-5.4	6.3
	45°	4.0	2.1	18.8	-3.6	11.5	-0.06	0.07	11.4	-0.3	0.21	0.06	0.03	5.1	-0.07	0.18	0.05	0.05	42.2	-0.1	0.2
Max Oper	0°	5.0	0.49	35.0	3.3	6.7	-0.15	0.02	18.3	-0.21	-0.08	0.22	0.21	4.7	-0.61	1.04	-4.9	0.12	8.1	-5.3	-4.4
	22.5°	5.0	0.49	37.0	3.4	6.7	-0.15	0.02	17.9	-0.21	-0.08	0.22	0.21	4.9	-0.61	1.04	-4.9	0.13	7.8	-5.4	-4.4
	45°	5.0	0.48	39.0	3.4	6.6	-0.15	0.02	17.9	-0.21	-0.09	0.21	0.21	4.9	-0.61	1.04	-4.9	0.11	8.0	-5.3	-4.4

Table F.43: Minimum Tendon Tensions during 50-year Environment and Maximum Operating Load Cases

Environment & Heading		Minimum Tension Tendon 1 N	Tendon 2 N	Tendon 3 N	Tendon 4 N	Tendon 5 N	Tendon 6 N	Tendon 7 N	Tendon 8 N
50-yr	0°	1.11E+06	1.25E+06	1.83E+06	1.89E+06	1.89E+06	1.83E+06	1.25E+06	1.11E+06
	22.5°	9.52E+05	1.05E+06	1.67E+06	1.76E+06	1.91E+06	1.90E+06	1.46E+06	1.28E+06
	45°	9.92E+05	1.01E+06	1.60E+06	1.75E+06	1.99E+06	1.99E+06	1.66E+06	1.50E+06
Max Oper	0°	9.10E+05	7.87E+05	1.18E+06	1.53E+06	1.82E+06	1.33E+06	3.54E+04	1.63E+05
	22.5°	9.38E+05	9.45E+05	8.41E+05	1.08E+06	2.22E+06	1.97E+06	1.29E+05	2.67E+04
	45°	6.31E+05	8.91E+05	6.94E+05	7.81E+05	2.08E+06	2.23E+06	5.29E+05	2.01E+05

Table F.44: Maximum Tendon Tensions during 50-year Environment and Maximum Operating Load Cases

Environment & Heading		Maximum Tension Tendon 1 N	Tendon 2 N	Tendon 3 N	Tendon 4 N	Tendon 5 N	Tendon 6 N	Tendon 7 N	Tendon 8 N
50-yr	0°	5.20E+06	5.24E+06	5.67E+06	5.79E+06	5.79E+06	5.67E+06	5.24E+06	5.20E+06
	22.5°	5.29E+06	5.30E+06	5.58E+06	5.69E+06	5.81E+06	5.71E+06	5.24E+06	5.23E+06
	45°	5.28E+06	5.29E+06	5.36E+06	5.42E+06	5.66E+06	5.64E+06	5.30E+06	5.26E+06
Max Oper	0°	3.82E+06	4.32E+06	5.63E+06	5.51E+06	4.75E+06	4.87E+06	4.45E+06	4.11E+06
	22.5°	3.42E+06	3.68E+06	5.54E+06	5.64E+06	4.73E+06	4.72E+06	4.80E+06	4.56E+06
	45°	3.55E+06	3.40E+06	5.13E+06	5.46E+06	5.04E+06	4.78E+06	4.95E+06	4.86E+06

Appendix G: Phase 1 Cost Estimates

Table G.1: Estimated Fabrication Costs – Phase 1 Design

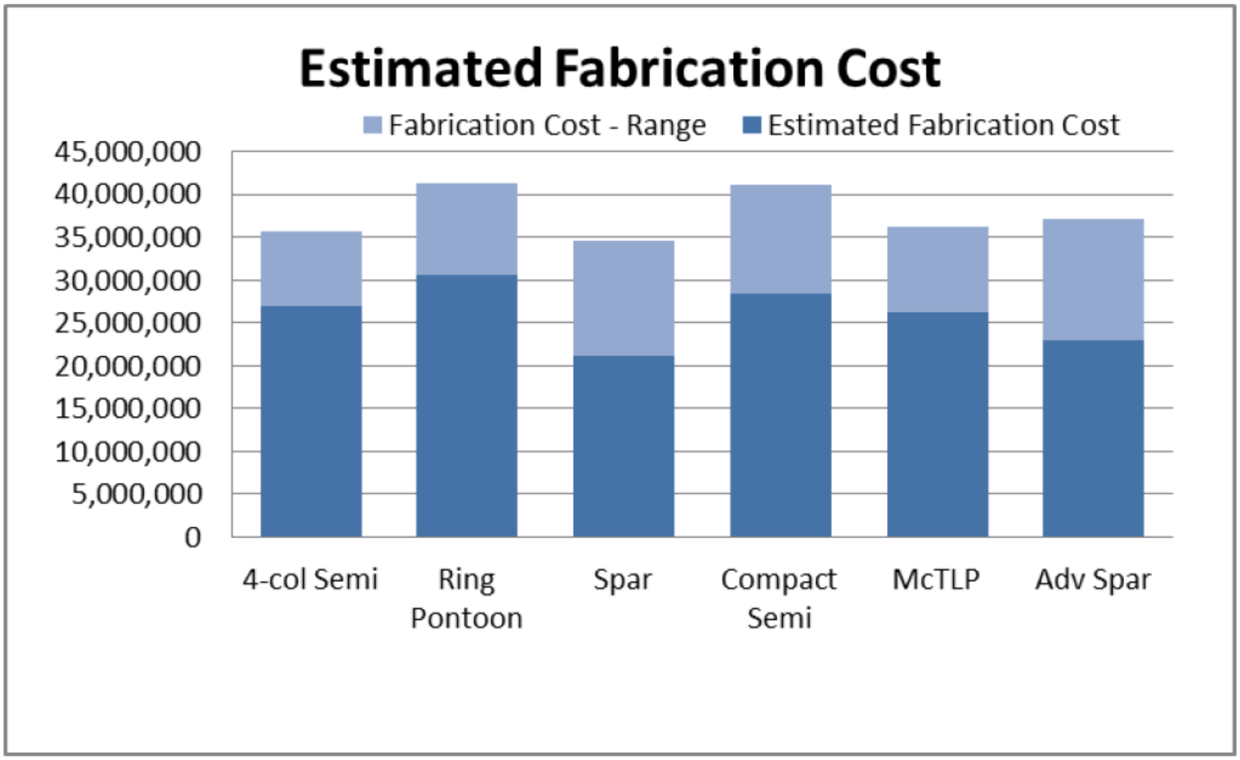


Table G.2: Estimated Procurement and Fabrication Costs – Phase 1 Design

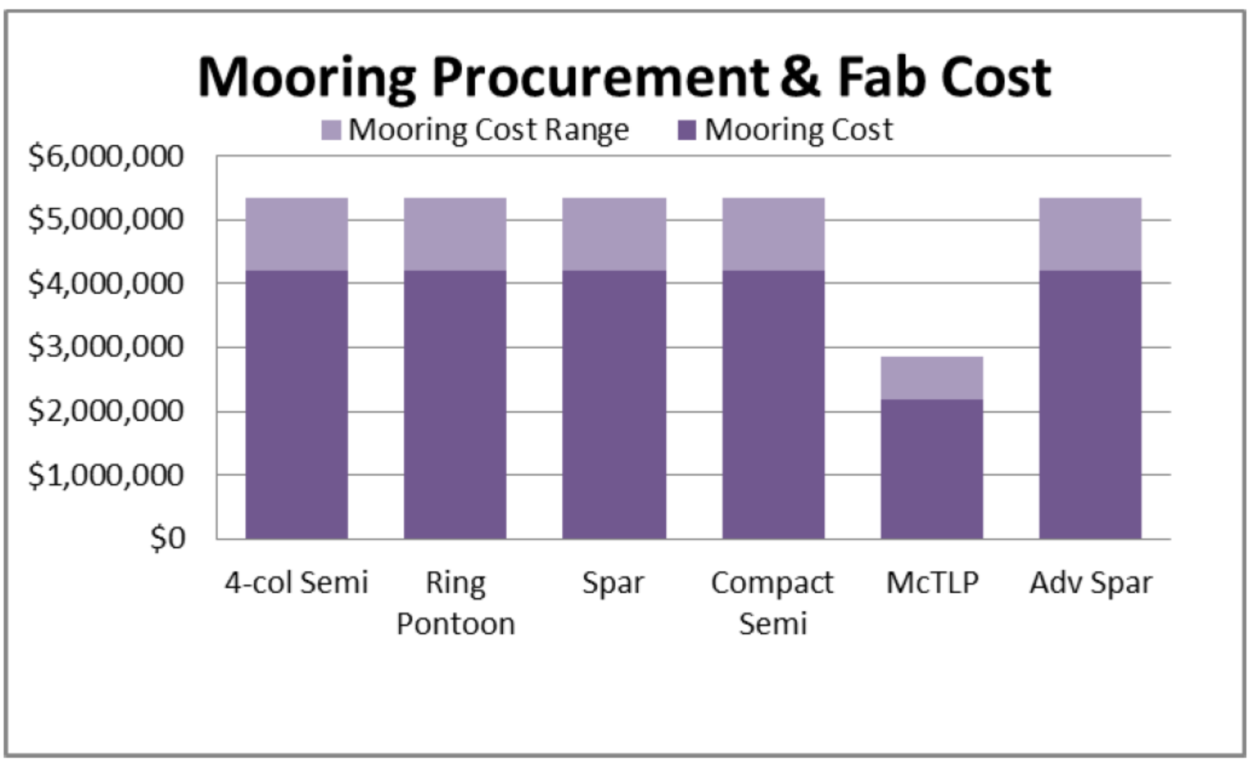


Table G.3: Estimated Installation Costs – Phase 1 Design

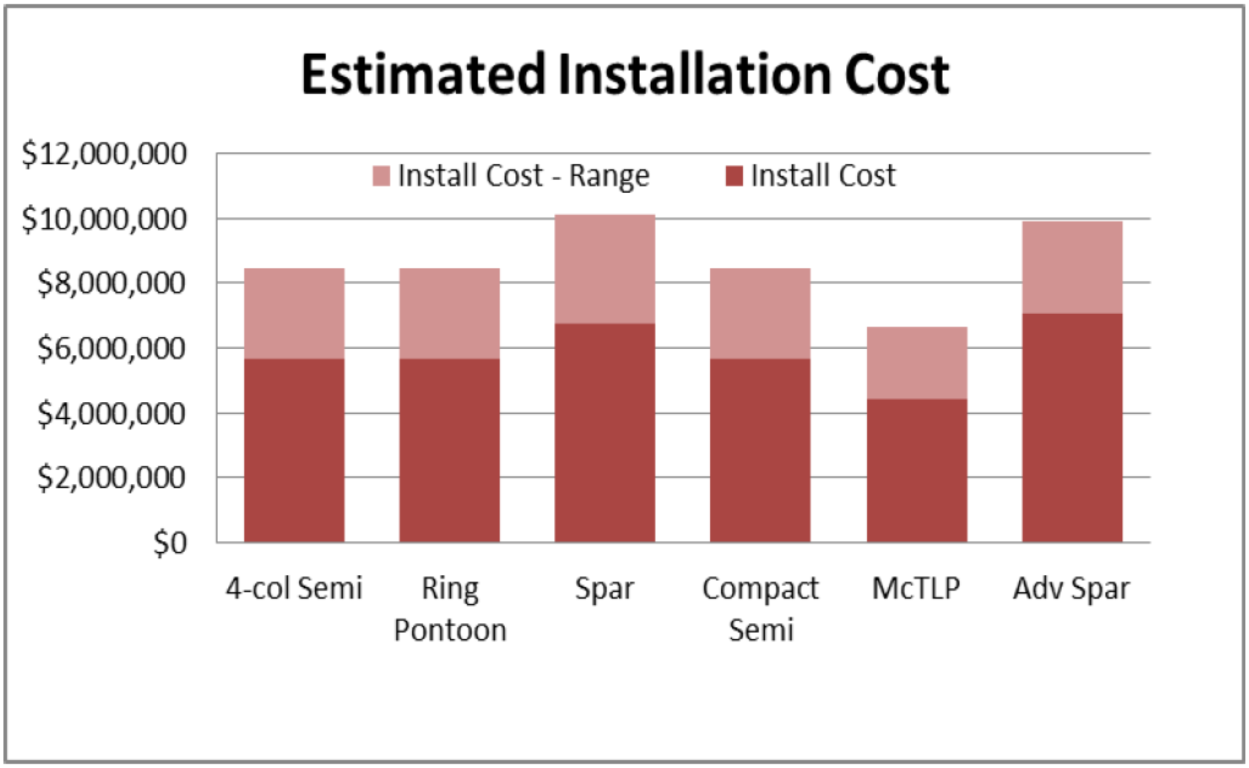
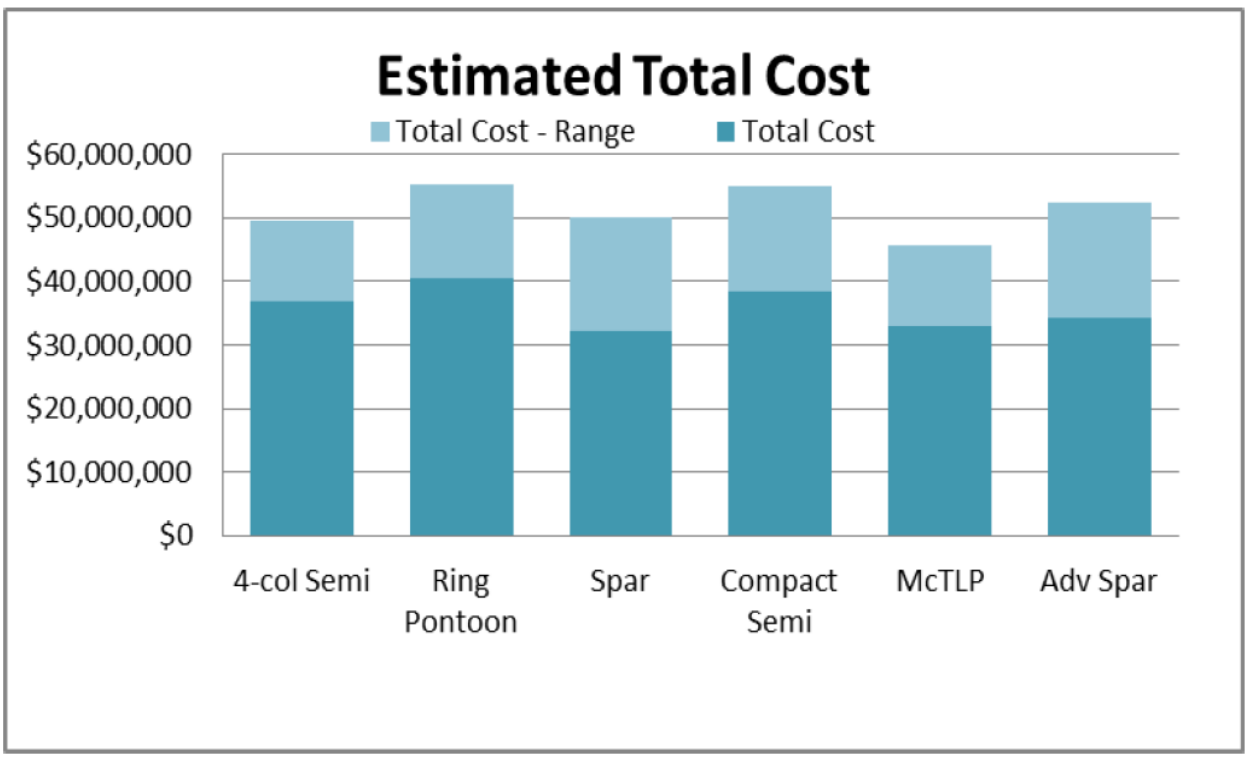


Table G.4: Estimated Procurement and Fabrication Costs – Phase 1 Design



Appendix H: Operating Loads at Rotor Base

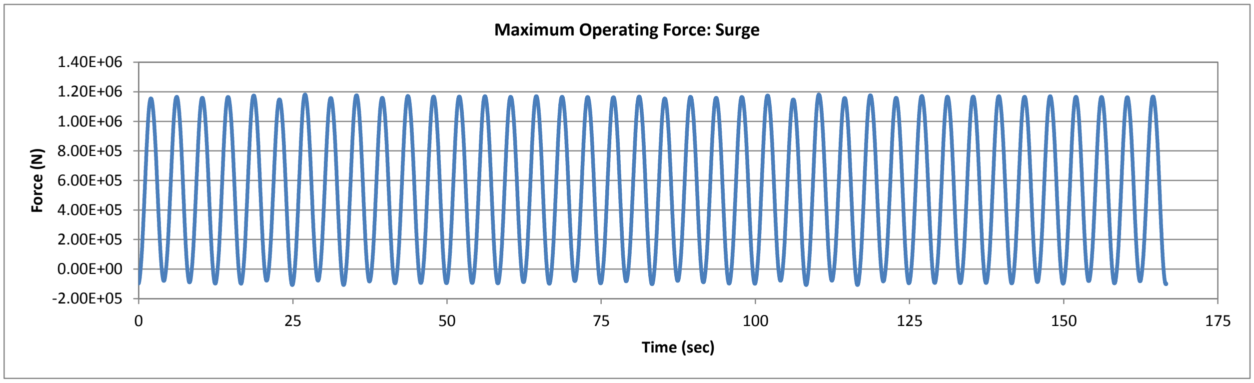


Figure H.1: Operating Force at Rotor Base: Surge

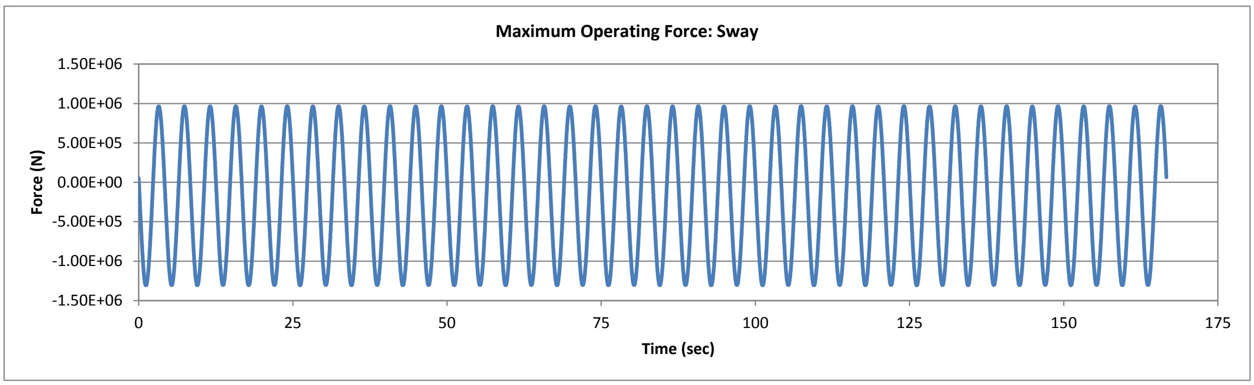


Figure H.2: Maximum Operating Force at Rotor Base: Sway

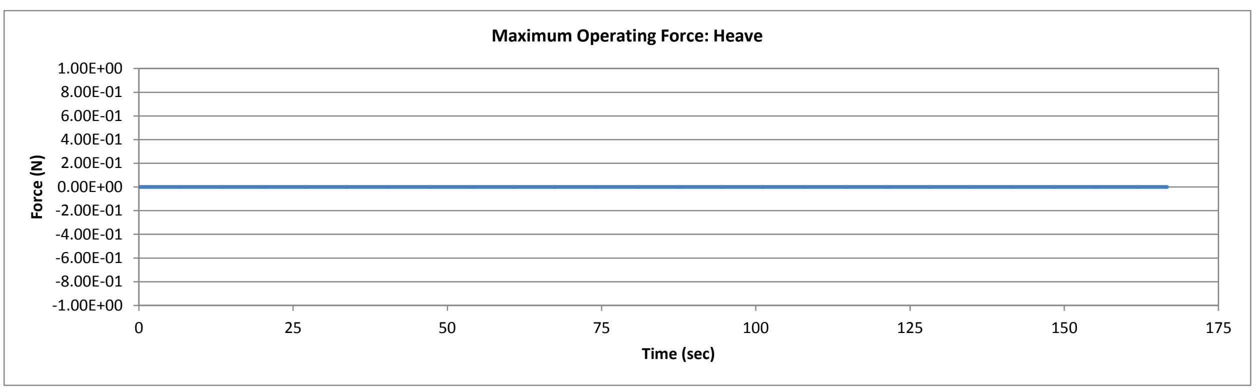


Figure H.3: Maximum Operating Force at Rotor Base: Heave

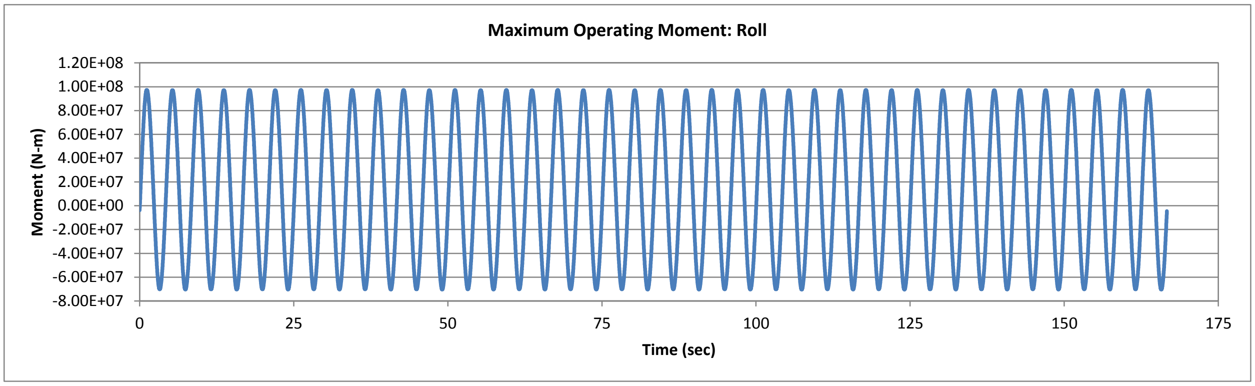


Figure H.4: Maximum Operating Moment at Rotor Base: Roll

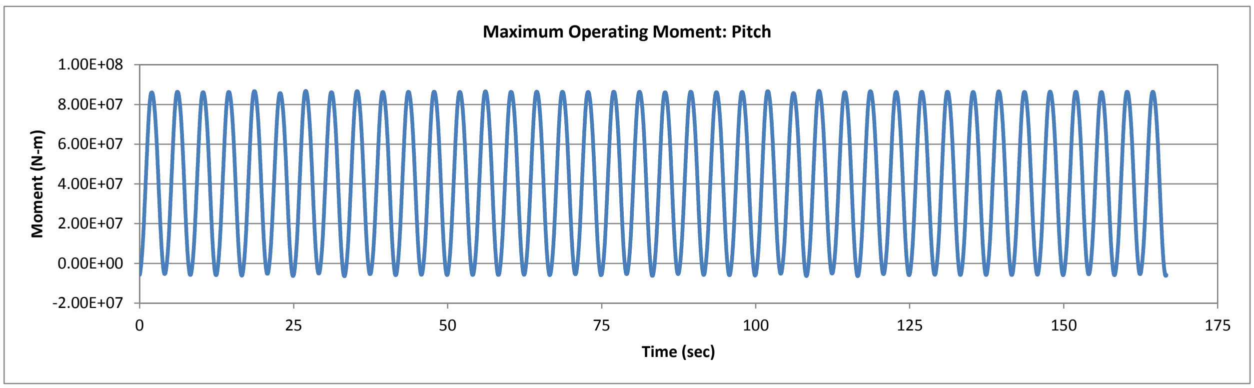


Figure H.5: Maximum Operating Moment at Rotor Base: Pitch

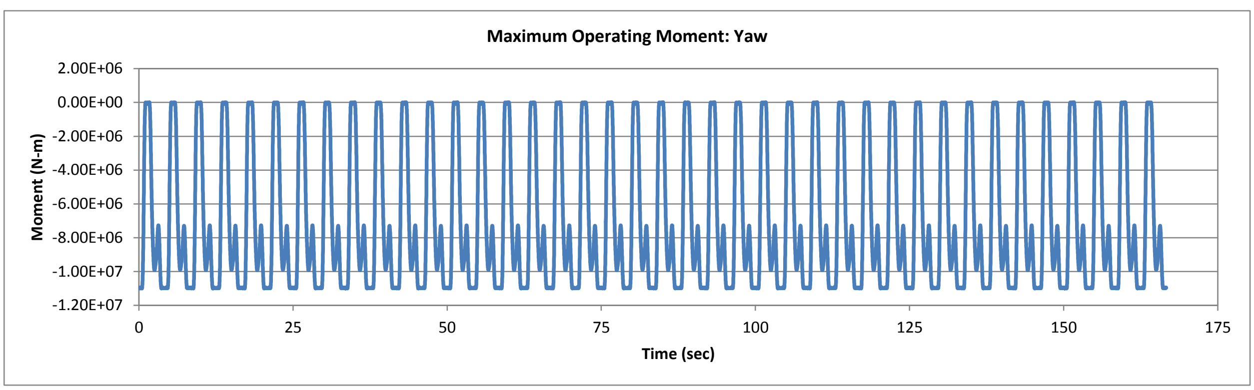


Figure H.6: Maximum Operating Moment at Rotor Base: Yaw

Table H.7: Mean Operating Loads at Rotor Base – 0-deg Environment Heading

Mean		
Surge	5.346835E+05	*N*
Sway	-1.747280E+05	*N*
Heave	0.000000E+00	*N*
Roll	1.327915E+07	*N-m*
Pitch	4.063885E+07	*N-m*
Yaw	-7.000322E+06	*N-m*

Table H.8: 2P Operating Loads at Rotor Base – 0-deg Environment Heading

Re			Im		
Surge	-6.262443E+05	*N*	**Surge**	-1.039433E+05	*N*
Sway	1.708906E+05	*N*	**Sway**	1.118103E+06	*N*
Heave	0.000000E+00	*N*	**Heave**	0.000000E+00	*N*
Roll	-1.240724E+07	*N-m*	**Roll**	-8.240116E+07	*N-m*
Pitch	-4.600418E+07	*N-m*	**Pitch**	-7.703478E+06	*N-m*
Yaw	-3.129178E+06	*N-m*	**Yaw**	-3.777271E+06	*N-m*

Table H.9: 4P Operating Loads at Rotor Base – 0-deg Environment Heading

Re			Im		
Surge	3.992846E+03	*N*	**Surge**	1.218313E+03	*N*
Sway	-5.164304E+03	*N*	**Sway**	-3.132328E+03	*N*
Heave	0.000000E+00	*N*	**Heave**	0.000000E+00	*N*
Roll	-1.919687E+05	*N-m*	**Roll**	-7.496527E+04	*N-m*
Pitch	-1.729322E+05	*N-m*	**Pitch**	-3.584943E+04	*N-m*
Yaw	-2.188157E+06	*N-m*	**Yaw**	2.180801E+06	*N-m*

Table H.10: Mean Operating Loads at Rotor Base – 22.5-deg Environment Heading

Mean		
Surge	5.608487E+05	*N*
Sway	4.318691E+04	*N*
Heave	0.000000E+00	*N*
Roll	-3.283475E+06	*N-m*
Pitch	4.262711E+07	*N-m*
Yaw	-7.000322E+06	*N-m*

Table H.11: 2P Operating Loads at Rotor Base – 22.5-deg Environment Heading

Re			Im		
Surge	-6.439713E+05	*N*	**Surge**	-5.239106E+05	*N*
Sway	-8.177098E+04	*N*	**Sway**	9.932150E+05	*N*
Heave	0.000000E+00	*N*	**Heave**	0.000000E+00	*N*
Roll	6.142240E+06	*N-m*	**Roll**	-7.318075E+07	*N-m*
Pitch	-4.725037E+07	*N-m*	**Pitch**	-3.865064E+07	*N-m*
Yaw	-3.129178E+06	*N-m*	**Yaw**	-3.777271E+06	*N-m*

Table H.12: 4P Operating Loads at Rotor Base – 22.5-deg Environment Heading

Re			Im		
Surge	5.665202E+03	*N*	**Surge**	2.324265E+03	*N*
Sway	-3.243199E+03	*N*	**Sway**	-2.427666E+03	*N*
Heave	0.000000E+00	*N*	**Heave**	0.000000E+00	*N*
Roll	-1.111777E+05	*N-m*	**Roll**	-5.553989E+04	*N-m*
Pitch	-2.332318E+05	*N-m*	**Pitch**	-6.180852E+04	*N-m*
Yaw	-2.188157E+06	*N-m*	**Yaw**	2.180801E+06	*N-m*

Table H.13: Mean Operating Loads at Rotor Base – 45-deg Environment Heading

	Mean	
Surge	5.016297E+05	*N*
Sway	2.545270E+05	*N*
Heave	-5.579928E+06	*N*
Roll	-1.934623E+07	*N-m*
Pitch	3.812579E+07	*N-m*
Yaw	-7.000322E+06	*N-m*

Table H.14: 2P Operating Loads at Rotor Base – 45-deg Environment Heading

	Re			Im	
Surge	-5.636595E+05	*N*	**Surge**	-8.641172E+05	*N*
Sway	-3.219837E+05	*N*	**Sway**	7.171191E+05	*N*
Heave	0.000000E+00	*N*	**Heave**	0.000000E+00	*N*
Roll	2.375662E+07	*N-m*	**Roll**	-5.281924E+07	*N-m*
Pitch	-4.130312E+07	*N-m*	**Pitch**	-6.371360E+07	*N-m*
Yaw	-3.129178E+06	*N-m*	**Yaw**	-3.777271E+06	*N-m*

Table H.15: 4P Operating Loads at Rotor Base – 45-deg Environment Heading

	Re			Im	
Surge	6.475083E+03	*N*	**Surge**	3.076368E+03	*N*
Sway	-8.283464E+02	*N*	**Sway**	-1.353413E+03	*N*
Heave	0.000000E+00	*N*	**Heave**	0.000000E+00	*N*
Roll	-1.346083E+04	*N-m*	**Roll**	-2.765907E+04	*N-m*
Pitch	-2.580239E+05	*N-m*	**Pitch**	-7.835782E+04	*N-m*
Yaw	-2.188157E+06	*N-m*	**Yaw**	2.180801E+06	*N-m*

Appendix I: Phase 2 Cost Estimates

Table I.1: Phase 2 Cost Estimate – Lower Bound

Revision	3
Case	Phase 2 - Lower Bound
Installation	150 m WD - Wire Rope TLP
Date	3/24/2017
Prepared	SRP

Item	Sub-Item	No.	Total (MM USD)	Unit of Measurement	Total Quantity	Unit Price (USD)	Item Cost (MM USD)	Notes
Hull			**18.092**	ton	3,192			
Project Costs			1.966	$/ton		616		Hull & Mooring only
	Project Management							
	Overhead							
	Profit							
	Engineering							Costs spread over 100 units
	Certification							Costs spread over 100 units
	Subtotal			$/ton		616		
Turbine Support Structure			0.950	ton	188	$ 5,052		
	Turbine Structural Interface							Connects turbine housing to hull
	Main Support Beams							Ties tops of columns together
	Secondary Bracing							Interconnects main support beams
	Deck Area							Space for temporary equipment
	Walkways, Handrails and Ladders							Access/Egress
	Subtotal			ton	188			
Interior Columns			3.645	ton	721.5	$ 5,052		
	Top Deck							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Keel Deck							Plate and stiffeners
	Subtotal				578			
	Anodes - External							Corrosion protection
	Manways, Walkways, Handrails and Ladders - Interna							Internal Access
	Subtotal				57.5			
	Shear Plates - Horizonta				17.3			Plates between columns
	Shear Plates - Vertical				69.2			Plates between columns
Outer Columns			11.532	ton	2,283	$ 5,052		
Upper Void Tank								
	Top Deck							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Subtotal			ton	927			
	Manways							Top of column access
	Walkways, Handrails and Ladders - Internal							Internal access
	Vents and Sounding Tubes - Internal							Reqd. by USCG
	Painting for Splash Zone - Externa							Corrosion protection
	Pneumatic Tubes							Pass through to ballast tank
	Subtotal			ton	93			
	Power Cable Guide - External (Single Column)							Prevents clashing
	Tendon Porches - External							Supports tensioners
	Ladder - External							Access/Egress
	Subtotal			ton	139			
Lower Void Tank								
	Deck - Upper							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Subtotal			ton	449			
	Manways							Lower Void Access
	Walkways, Handrails and Ladders - Internal							Internal access
	Vents and Sounding Tubes							Reqd. by USCG
	Painting for Splash Zone - Externa							Corrosion protection
	Pneumatic Tubes							Pass through to ballast tank
	Subtotal			ton	45			
	Anodes - External							Corrosion protection
	Barge Fenders - Externa							Collision protection
	Personnel Transfer Structure - Externa							Access & Egress from workboat
	Tow Bollards - External							Reqd. for towing
	Power Cable Guide - External (Single Column)							Prevents clashing
	Subtotal			ton	67			
Variable Ballast Tank								
	Deck - Upper							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Keel Deck							Plate and stiffeners
	Subtotal			ton	449			
	Anodes - Internal							Corrosion protection
	Seachest							Allows ingress & egress of seawater ballast
	Pneumatic Tubes							Allows pressure to change ballast
	Subtotal			ton	45			
	Anodes - External							Corrosion protection
	Tow Bollards - External							Connects to tow line
	Bellmouth							Power Cable(Single Column)
	Bellmouths							Tendons
	Subtotal			ton	67			
Hull Equipment								
	Ballast Tank Pressure Monitoring System							Not included
	Tendon Tension Monitoring System							Not included
	Air Compressor							Not included
Tendon System			**2.178**					
Tendon Assemblies		8	0.915		4068	$ 225	$ 0.915	
	Top Tensioners							Mechanical, manually operated
	Top Connectors							Connect wire rope tendon to tensioner
	Wire Ropes							Upper tendons with fittings
	Spacer Assemblies							Prevents clashing
	Subsea Buoys							Supports lower portion of tendons
	Subsea Connection							ROV operated
	Wire Ropes							Lower tendons
	Bottom Connectors							Connects lower tendon to ball grab
	Ball Grabs							Connects tendon to foundation
	Subtotal			ft	4068	$ 225	$ 0.915	
Templates/Piles		8	1.263		400	$ 3,157	$ 1.263	
Foundation Templates								
	Structural Framing							Mounted to pile top
	Ball Grab Receptacles							Connects foundation to tendon
	Anodes							Corrosion protection
Piles								
	Suction Valves							ROV operated
	Steel Suction Piles							Provides resistance to tendon tension
	Subtotal			ton	400	$ 3,157	$ 1.263	

Item	Sub-Item	Days	Total (MM USD)	Mobilization (USD)	Fuel/Day (USD)	Day Rate (USD)	Item Cost (MM USD)	Notes
Installation			**4.184**					
	Anchor Handling Vessel with ROV	3		3,200		$ 160,000	0.483	Install anchor piles spread over 100 units
	3 Ocean Tugs (2 in front, 1 trail)	2		480,000	32,800	$ 240,000	1.026	Tow of hull to site
	Anchor Handling Vessel	2				$ 160,000	$ 0.320	Connection of hull to piles
	3 Ocean Tugs (2 in front, 1 trail)	2			32,800	$ 240,000	$ 0.546	Connection of hull to piles
	Anchor Handling Vessel w/ROV	1				$ 160,000	$ 0.160	Connect Power Cable
	Anchor Handling Vessel	1				$ 160,000	$ 0.160	Ballast hull to set tensions
	Anchor Handling Vessel	1				$ 160,000	$ 0.160	Remove hull equipment
	Anchor Handling Vessel	1		320000		$ 160,000	$ 0.480	Start up VAWT & De-mob AHV
							$ 0.150	Harbor movements
	Subtotal	13				$ 40,000	$ 0.520	Crews & equipment
							$ 0.180	Work, messenger wires, attachments
Grand Total			**24.454**					

Table I.2: Phase 2 Cost Estimate – Upper Bound

Revision	3
Case	Phase 2 - Upper Bound
Installation	150 m WD - Wire Rope TLP
Date	3/24/2017
Prepared	SRP

Item	Sub-Item	No.	Total (MM USD)	Unit of Measurement	Total Quantity	Unit Price (USD)	Item Cost (MM USD)	Notes
Hull			**24.887**	ton	3,192			
Project Costs			2.704	$/ton		847		Hull & Mooring only
	Project Managemen							
	Overheac							
	Profit							
	Engineering							Costs spread over 100 units
	Certification							Costs spread over 100 units
	Subtotal			$/ton		847		
Turbine Support Structure			1.307	ton	188	$ 6,950		
	Turbine Structural Interface							Connects turbine housing to hull
	Main Support Beams							Ties tops of columns together
	Secondary Bracing							Interconnects main support beams
	Deck Area							Space for temporary equipment
	Walkways, Handrails and Ladders							Access/Egress
	Subtotal			ton	188			
Interior Columns			5.014	ton	721.5	$ 6,950		
	Top Deck							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Keel Deck							Plate and stiffeners
	Subtotal				578			
	Anodes - Externa							Corrosion protection
	Manways, Walkways, Handrails and Ladders - Interna							Internal Access
	Subtotal				57.5			
	Shear Plates - Horizonta				17.3			Plates between columns
	Shear Plates - Vertical				69.2			Plates between columns
Outer Columns			15.863	ton	2,283	$ 6,950		
Upper Void Tank								
	Top Deck							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Subtotal			ton	927			
	Manways							Top of column access
	Walkways, Handrails and Ladders - Interna							Internal access
	Vents and Sounding Tubes - Interna							Reqd. by USCG
	Painting for Splash Zone - Externa							Corrosion protection
	Pneumatic Tubes							Pass through to ballast tank
	Subtotal			ton	93			
	Power Cable Guide - External (Single Column							Prevents clashing
	Tendon Porches - Externa							Supports tensioners
	Ladder - Externa							Access/Egress
	Subtotal			ton	139			
Lower Void Tank								
	Deck - Upper							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Subtotal			ton	449			
	Manways							Lower Void Access
	Walkways, Handrails and Ladders - Interna							Internal access
	Vents and Sounding Tubes							Reqd. by USCG
	Painting for Splash Zone - Externa							Corrosion protection
	Pneumatic Tubes							Pass through to ballast tank
	Subtotal			ton	45			
	Anodes - Externa							Corrosion protection
	Barge Fenders - Externa							Collision protection
	Personnel Transfer Structure - Externa							Access & Egress from workboat
	Tow Bollards - Externa							Reqd. for towing
	Power Cable Guide - External (Single Column							Prevents clashing
	Subtotal			ton	67			
Variable Ballast Tank								
	Deck - Upper							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Keel Deck							Plate and stiffeners
	Subtotal			ton	449			
	Anodes - Internal							Corrosion protection
	Seachest							Allows ingress & egress of seawater ballast
	Pneumatic Tubes							Allows pressure to change ballast
	Subtotal			ton	45			
	Anodes - Externa							Corrosion protection
	Tow Bollards - Externa							Connects to tow line
	Bellmouth							Power Cable(Single Column)
	Bellmouths							Tendons
	Subtotal			ton	67			
Hull Equipment								
	Ballast Tank Pressure Monitoring System							Not included
	Tendon Tension Monitoring System							Not included
	Air Compressor							Not included
Tendon System			**2.855**					
Tendon Assemblies		8	1.119		4068	$ 275	$ 1.119	
	Top Tensioners							Mechanical, manually operated
	Top Connectors							Connect wire rope tendon to tensioner
	Wire Ropes							Upper tendons with fittings
	Spacer Assemblies							Prevents clashing
	Subsea Buoys							Supports lower portion of tendons
	Subsea Connection							ROV operated
	Wire Ropes							Lower tendons
	Bottom Connectors							Connects lower tendon to ball grab
	Ball Grabs							Connects tendon to foundation
	Subtotal			ft	4068	$ 275	$ 1.119	
Templates/Piles		8	1.736		400	$ 4,341	$ 1.736	
Foundation Templates								
	Structural Framing							Mounted to pile top
	Ball Grab Receptacles							Connects foundation to tendon
	Anodes							Corrosion protection
Piles								
	Suction Valves							ROV operated
	Steel Suction Piles							Provides resistance to tendon tension
	Subtotal			ton	400	$ 4,341	$ 1.736	

Item	Sub-Item	Days	Total (MM USD)	Mobilization (USD)	Fuel/Day (USD)	Day Rate (USD)	Item Cost (MM USD)	Notes
Installation			**6.276**					
	Anchor Handling Vessel with ROV	3		4,800		$ 240,000	0.725	Install anchor piles spread over 100 units
	3 Ocean Tugs (2 in front, 1 trail)	2		720,000	49,200	$ 360,000	1.538	Tow of hull to site
	Anchor Handling Vesse	2				$ 240,000	$ 0.480	Connection of hull to piles
	3 Ocean Tugs (2 in front, 1 trail)	2			49,200	$ 360,000	$ 0.818	Connection of hull to piles
	Anchor Handling Vessel w/ROV	1				$ 240,000	$ 0.240	Connect Power Cable
	Anchor Handling Vessel	1				$ 240,000	$ 0.240	Ballast hull to set tensions
	Anchor Handling Vesse	1				$ 240,000	$ 0.240	Remove hull equipment
	Anchor Handling Vesse	1		480000		$ 240,000	$ 0.720	Start up VAWT & De-mob AHV
							$ 0.224	Harbor movements
	Subtotal	13				$ 60,000	$ 0.780	Crews & equipment
							$ 0.270	Work, messenger wires, attachments
Grand Total			**34.018**					

Basis of Phase 2 Cost Estimate

- Phase 1 Selection of Candidate Hull Form and Mooring Configuration –Wire Rope TLP
- Additional engineering effort included:
  - Updated Turbine Loading Data
  - Spreadsheet Re-Design
  - Application of Historical Weight Density Factors
  - Re-evaluation of Hydrostatics
  - Verification of Stability
  - Calculation of Natural Periods

Basic Assumptions in Phase 2 Cost Estimate

The following reflect differences from the Phase 1 Estimate:

- Efficiency gained from constructing multiple (100) units
  - Although it is not possible to precisely quantify this efficiency, it is prudent to include some benefit since there will certainly be some effect from mass production
- Overhead costs that can be spread over multiple units (100)
  - Engineering and some project management and certification
  - Anchor pile mobilization

Basic Assumptions in Phase 2 Cost Estimate

The range in the costs are intended to reflect:

- Anticipated discounts from the large volume of steel required for the wind farm (> 300,000 tonne)
- Potential savings from the use of typical industry specifications in lieu of customized specifications
- Acknowledgement that the VAWT platforms will typically be un-manned
- Uncertainty of geotechnical parameters
- Offshore construction vessel availability
- Potential use of bridge industry wire rope fittings

Type of Cost Estimate

Type 3 Cost Estimate based on the Cost Estimate Classification System – AACE International RP 17R-97

Estimate Class	Level of Project Definition	End Usage	Expected Accuracy Range	Preparation Effort
5	0 to 2%	Screening or Feasibility	+/- 50%	Minimal
4	1 to 15 %	Feasibility or Concept Study	+/- 35%	
3	10 to 40%	Budgetary or Control	+/- 25%	
2	30 to 70 %	Control or Bid Tender	+/- 15%	
1	50 to 100%	Check Estimate or Bid Tender	+/- 10%	Maximal

- The expected accuracy range of this estimate is ~ +/- 20%

Aspects Included in Cost Estimate

Construction of Hull and Turbine Support Structures

- Materials-Bulks and Equipment
- Fabrication-Labor and Equipment
- Project Management, Overhead and Profit
- Engineering
- Certification

Procurement and Fabrication of Mooring System

- Procurement of Wire Rope and Terminations
- Procurement of Tendon Connectors, Tensioners, Ball Grabs, Buoyancy
- Materials & Fabrication of Suction Piles

Aspects Included in Cost Estimate

Tow Out of Floating Platform and Connection to Moorings

- Installation of Anchor Piles and Lower Tendon Sections
- Tow of Floating Platform to Site with VAWT Installed
- Connection of Upper and Lower Tendons
- Connection of Subsea Transmission Cable
- Ballasting of Platform to Operating Draft
- Removal of Installation Equipment

Aspects Implicit in Cost Estimate

Estimated Percentages for Materials included in the Fabrication Cost

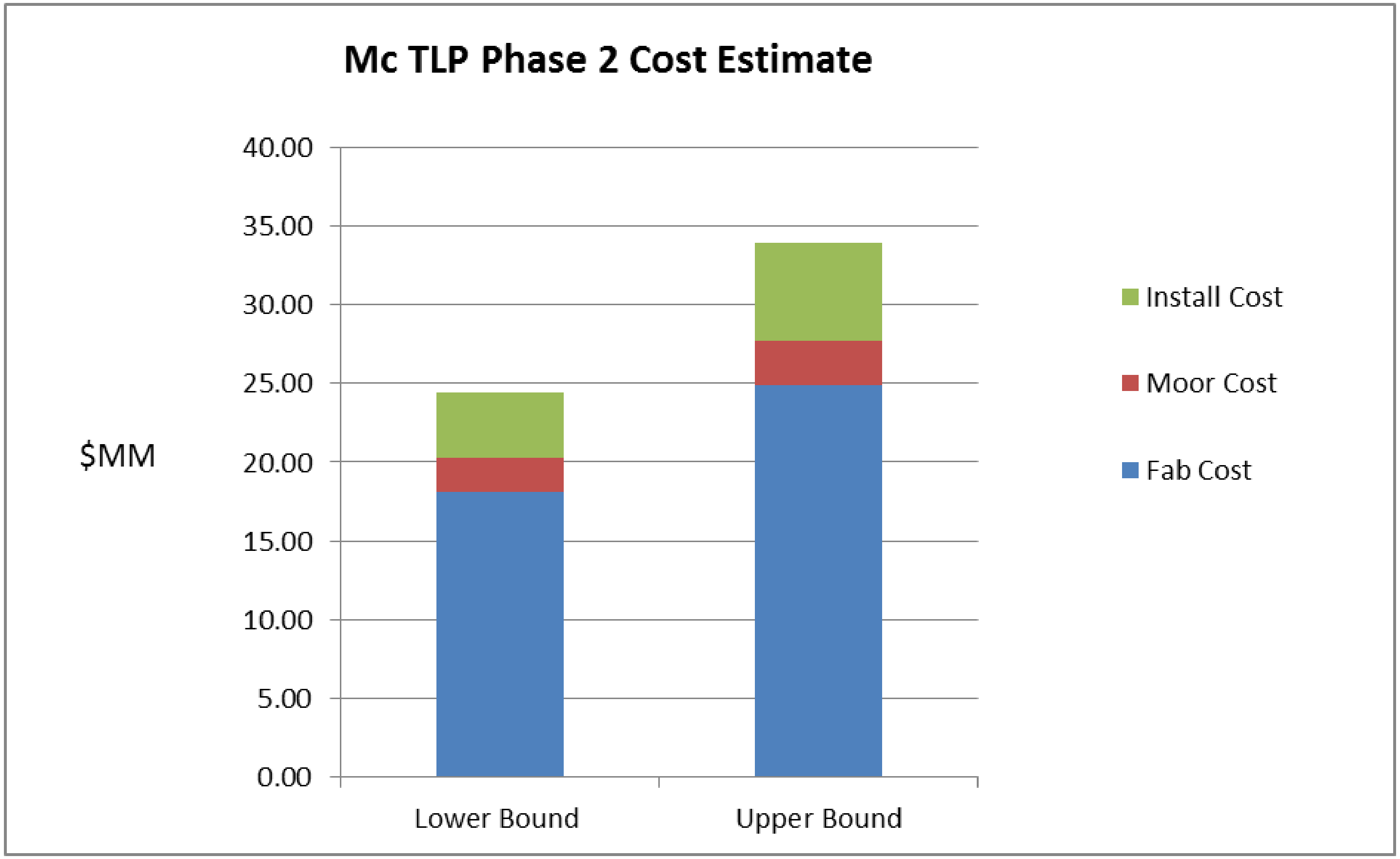
• Mooring Lines	75%-85%
• Anchor Piles	25%-30%
• Cylindrical Cells	20%-25%
• Special Substructures	5%-10%

Note - There are also some costs associated with offloading, handling, storage, disposal (reels), duties, taxes, etc. even for such things as wire rope tendons, which require minimal fabrication.

Aspects not Covered by Cost Estimate

- Costs of Pre-Construction Activities, such as:
  - Contractor(s) Selection
  - Prototype Testing, Licensing and Permitting
  - Preparation of Dry Dock(s)
  - Seafloor Geo-Hazard and Geotechnical Survey
  - Fabrication Method e.g., Crane Requirements
  - Dredging of Towing Channel (if required)
- Laying of Transmission Cable to Wind Farm Site
- Hook-up and Commissioning of Turbine System
- Inflation
- Market Conditions
- Role of US Government (if any)

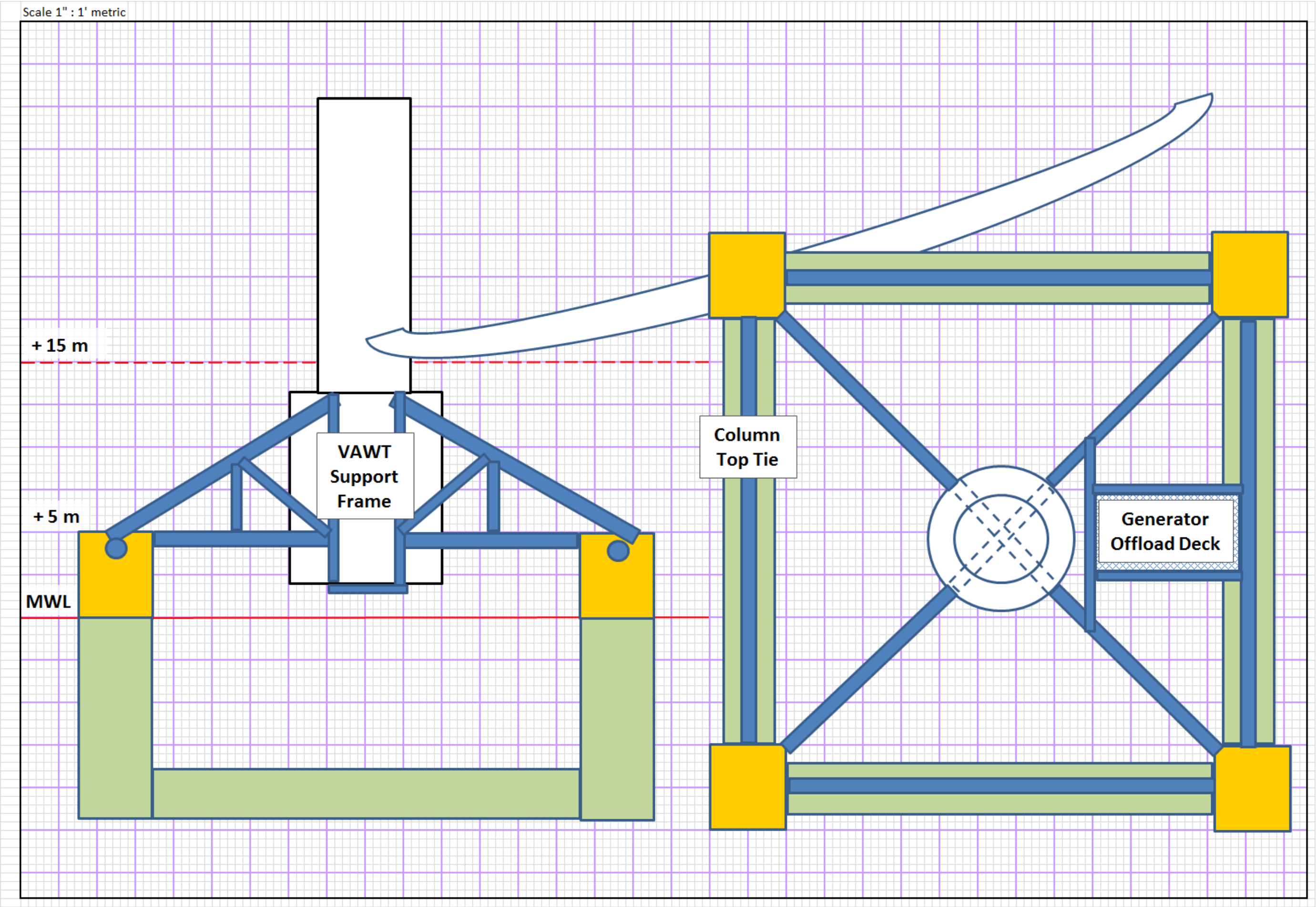
Offshore VAWT Platform Estimated Cost



- Total Cost Est. per MW $4.89 mm/MW - $6.80 mm/MW

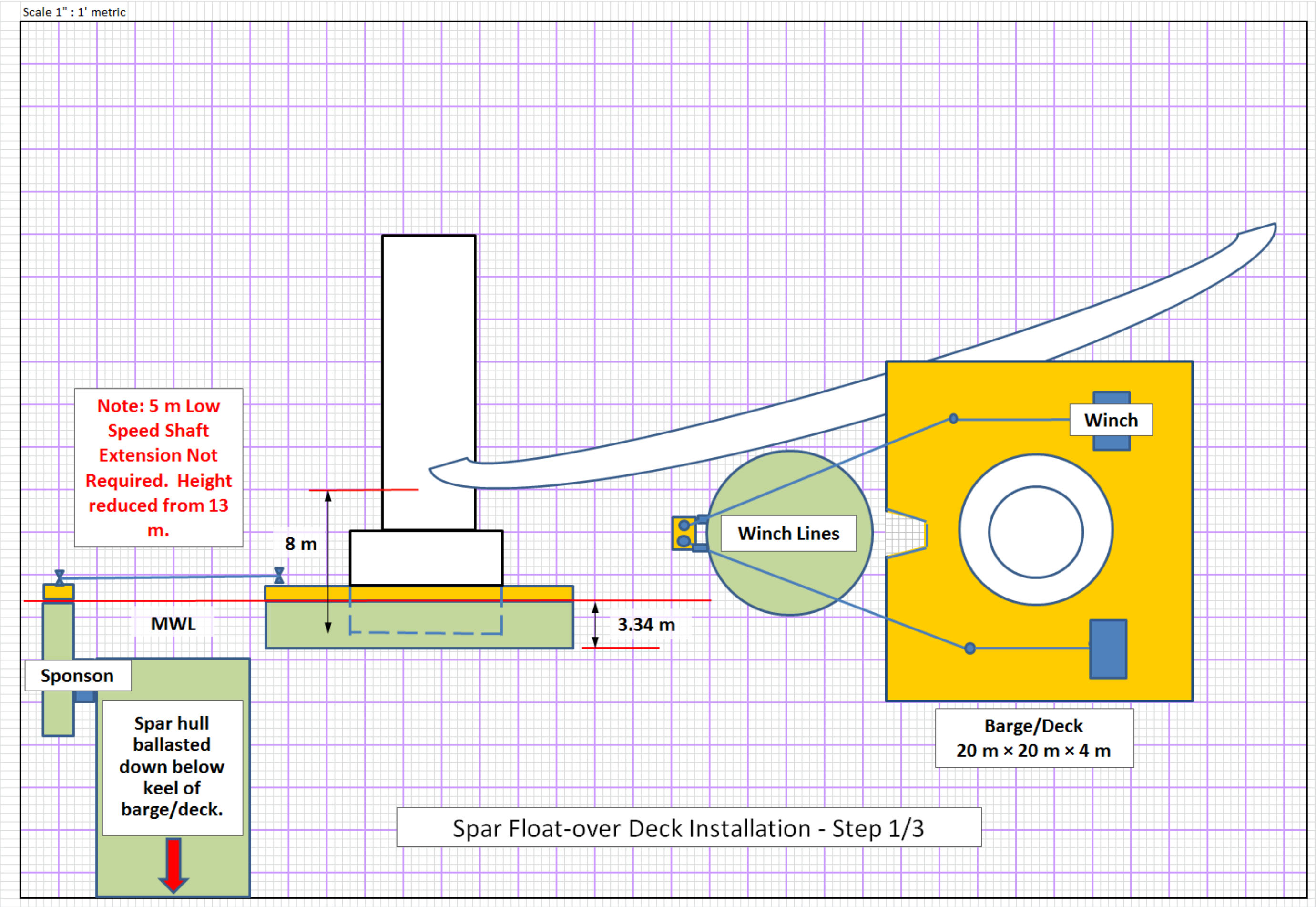
Appendix J: Logistical Considerations

Deck Steel for Four-column Semi



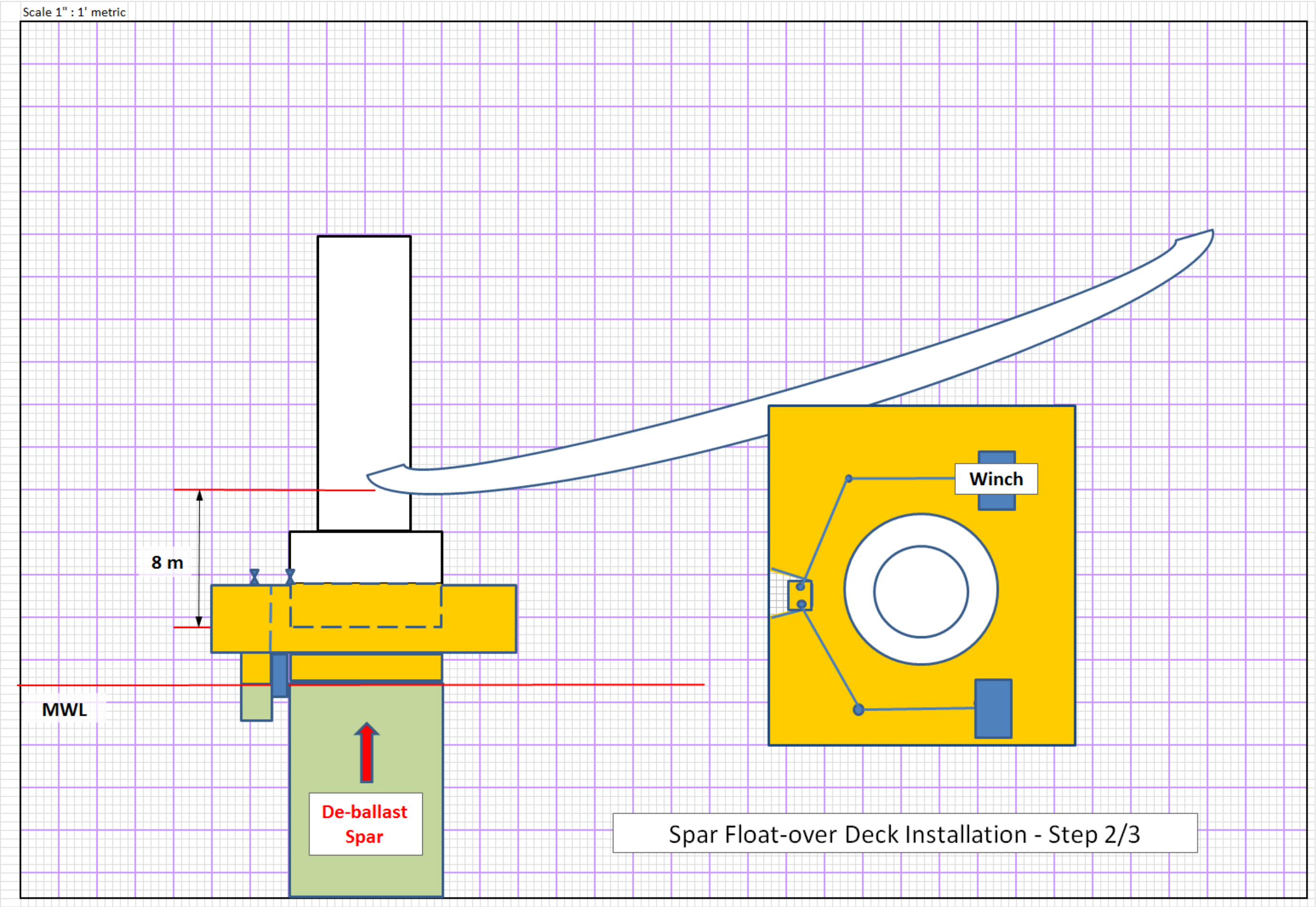
Preliminary Sketch: For Discussion Purposes Only

Classic Spar Float-over Deck (1/3)



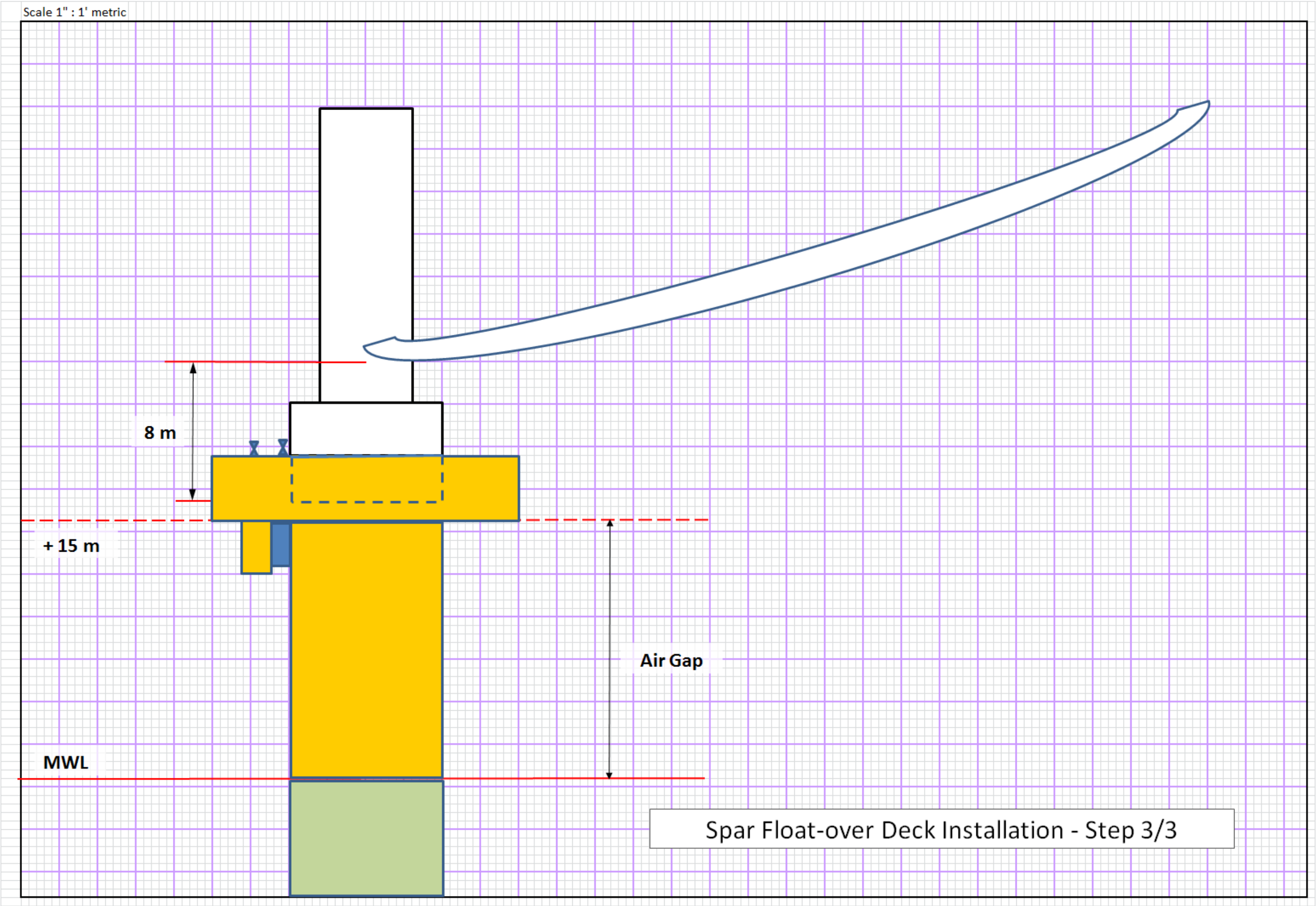
Logistical Considerations

Classic Spar Float-over Deck (2/3)



Preliminary Sketch: For Discussion Purposes Only

Classic Spar Float-over Deck (3/3)



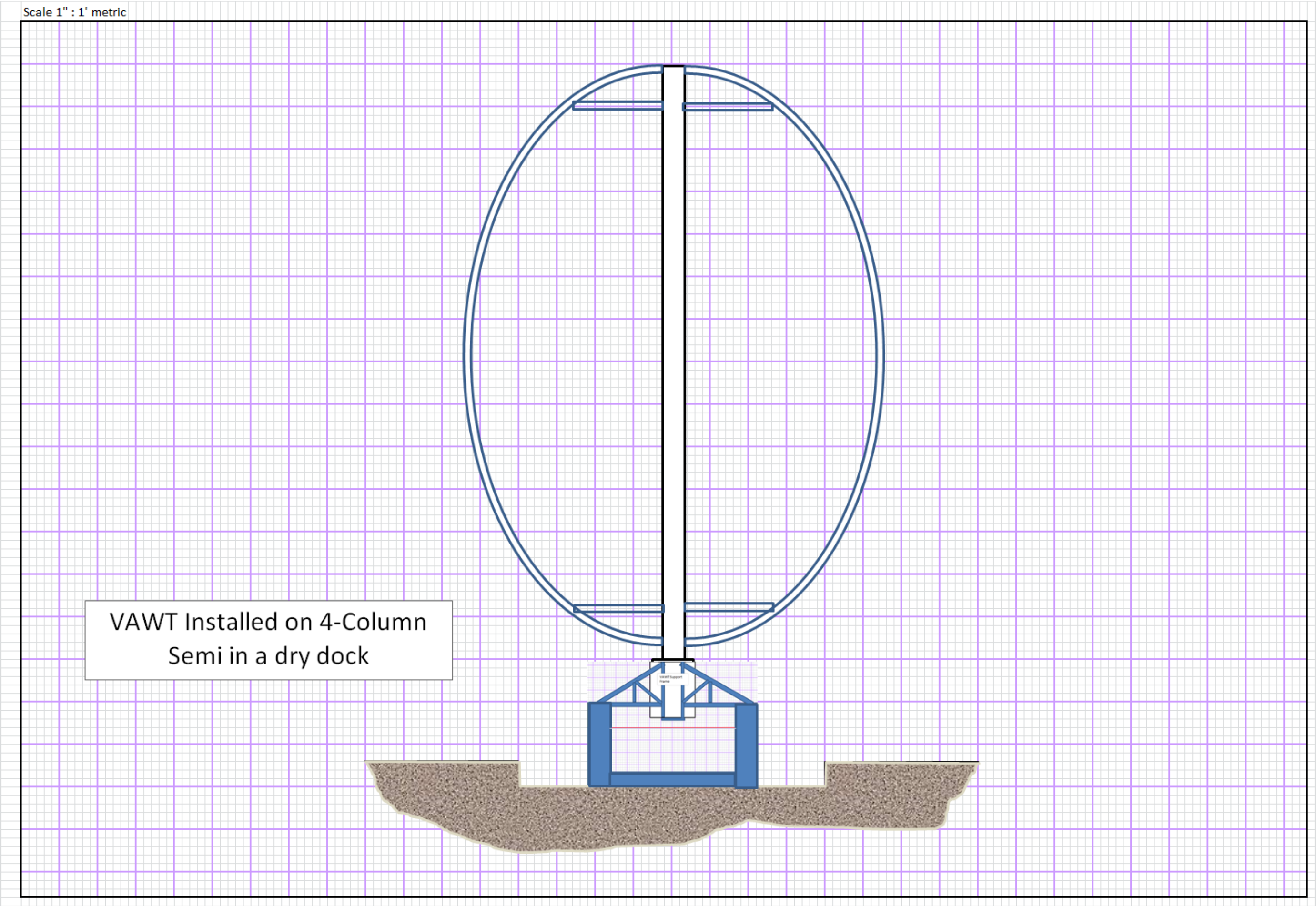
STRESS ENGINEERING SERVICES INC.

Preliminary Sketch: For Discussion Purposes Only

an employee-owned company

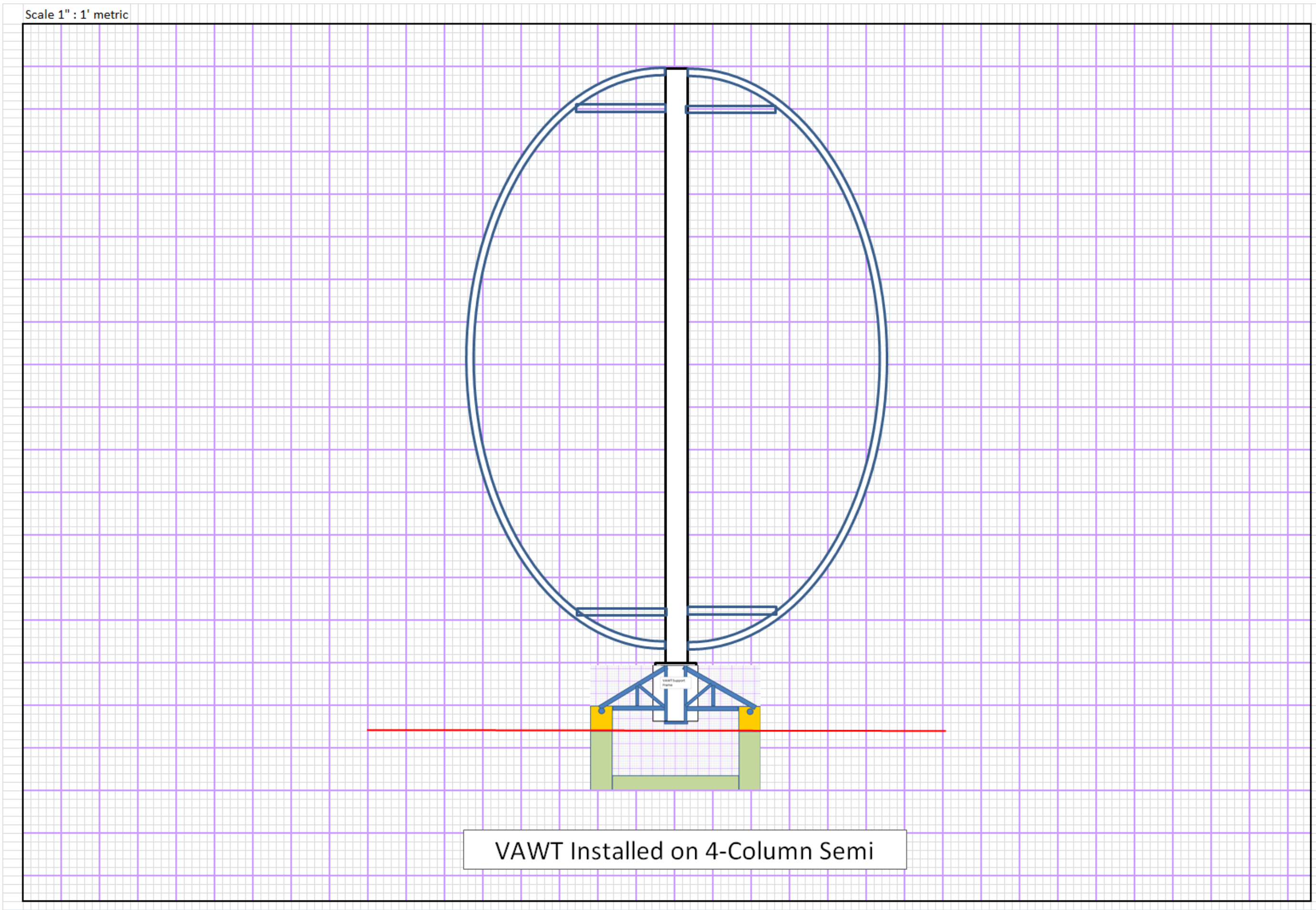
Logistical Considerations

VAWT Installation in Dry Dock



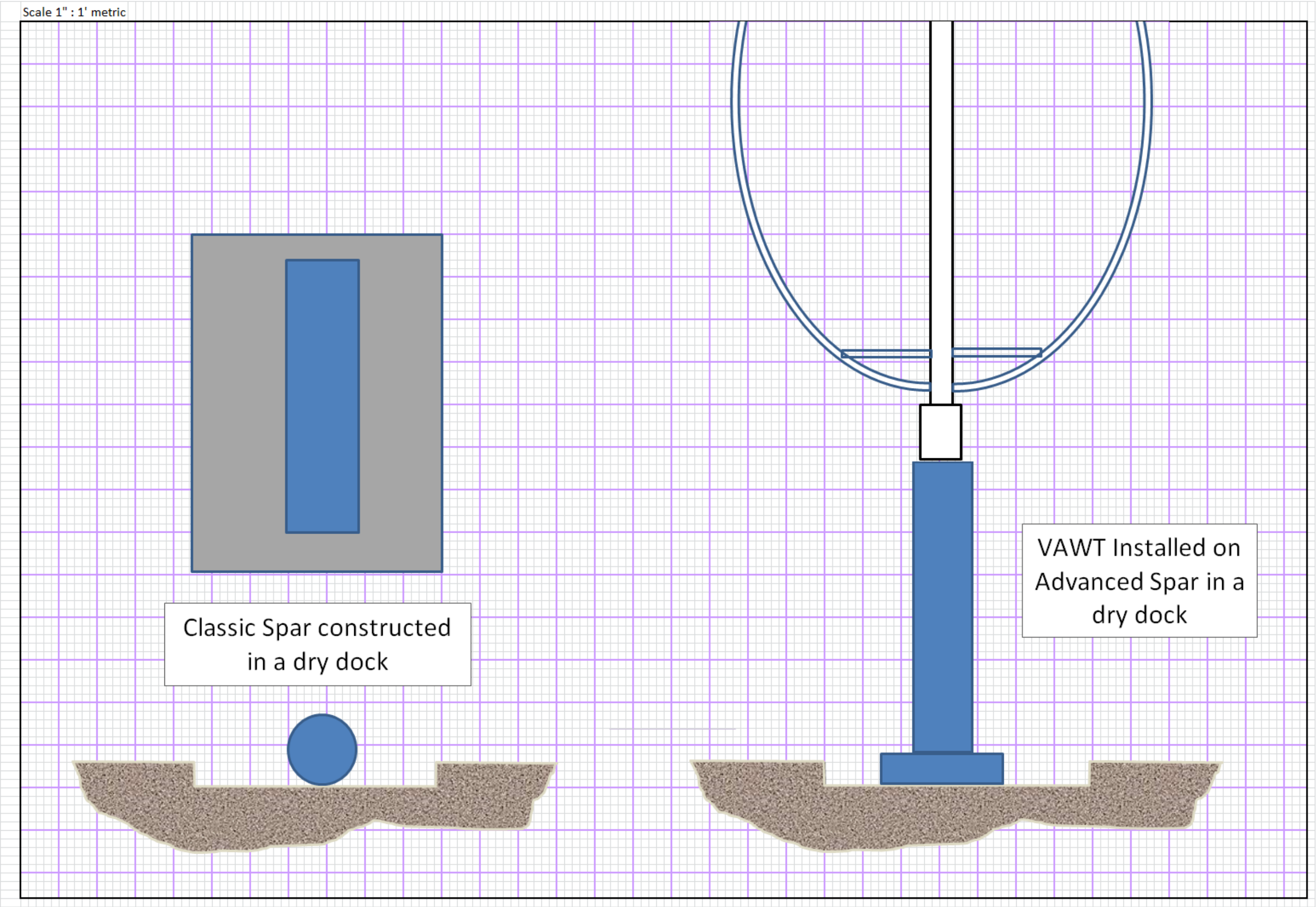
Preliminary Sketch: For Discussion Purposes Only

Installed Four-column Semi



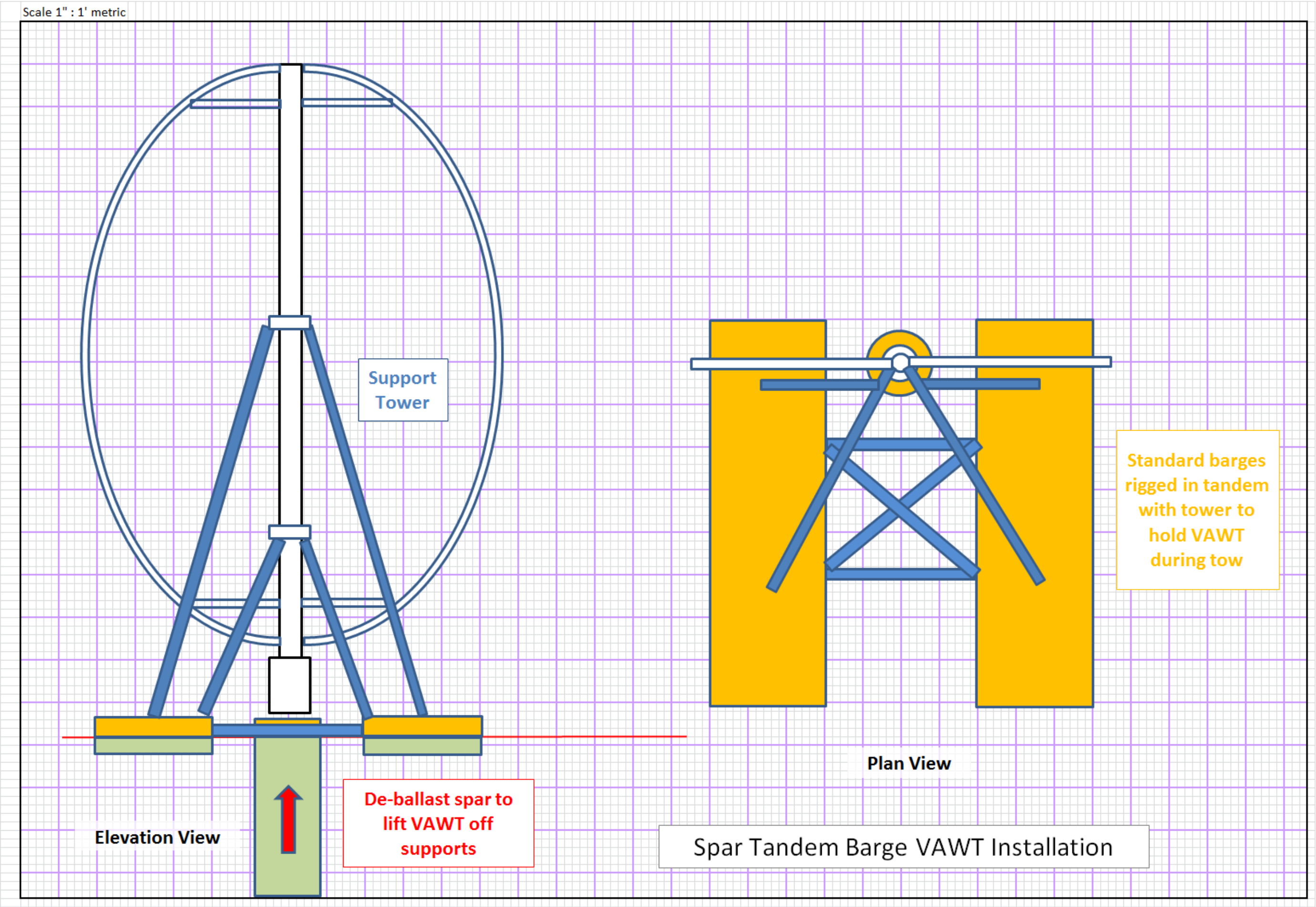
Preliminary Sketch: For Discussion Purposes Only

Classic Spar vs Advanced Spar in Dry Dock



Logistical Considerations

Spar Tandem Barge for VAWT Installation

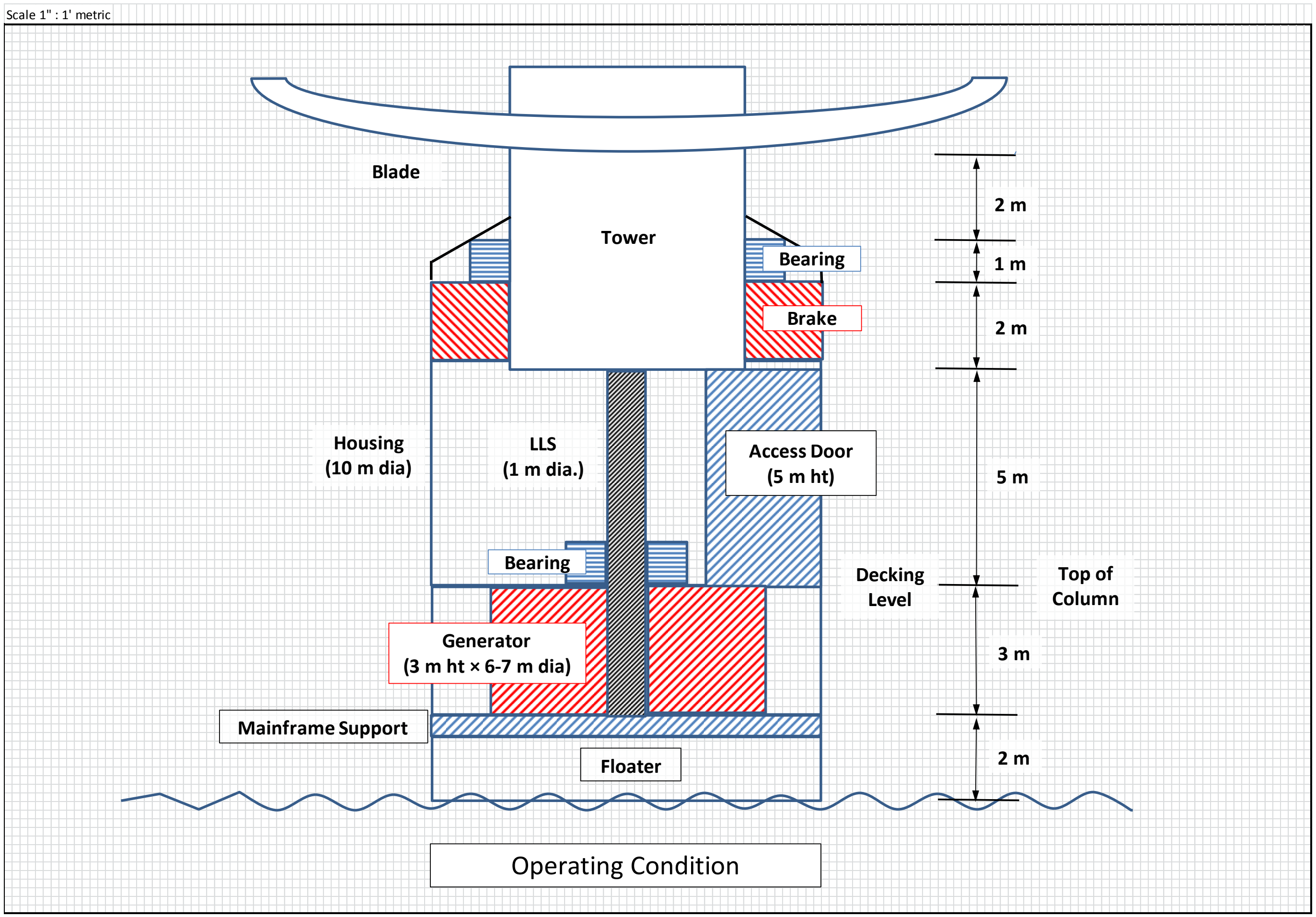


Preliminary Sketch: For Discussion Purposes Only

Logistical Considerations

Generator Removal

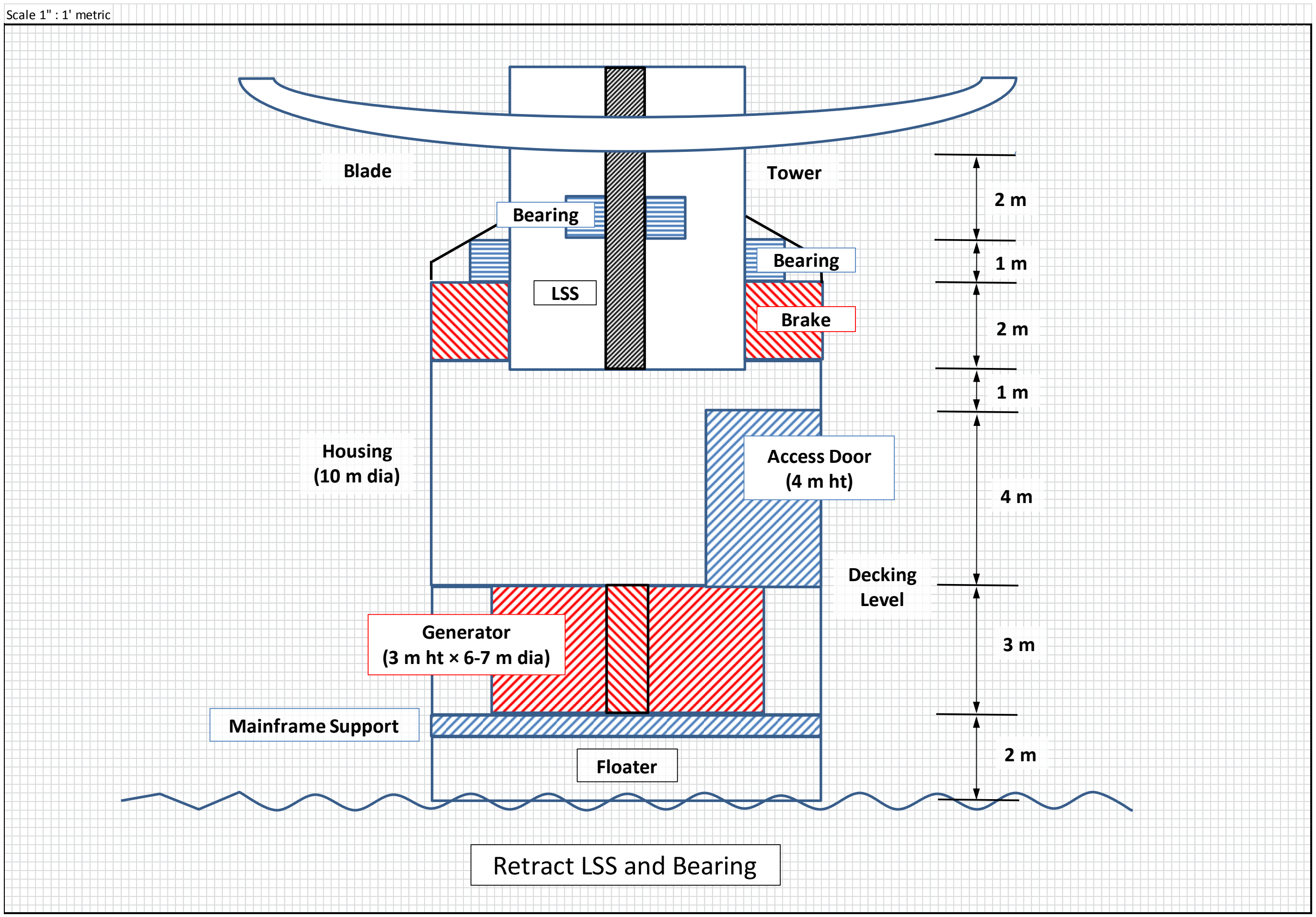
Step A



Logistical Considerations

Generator Removal

Step B

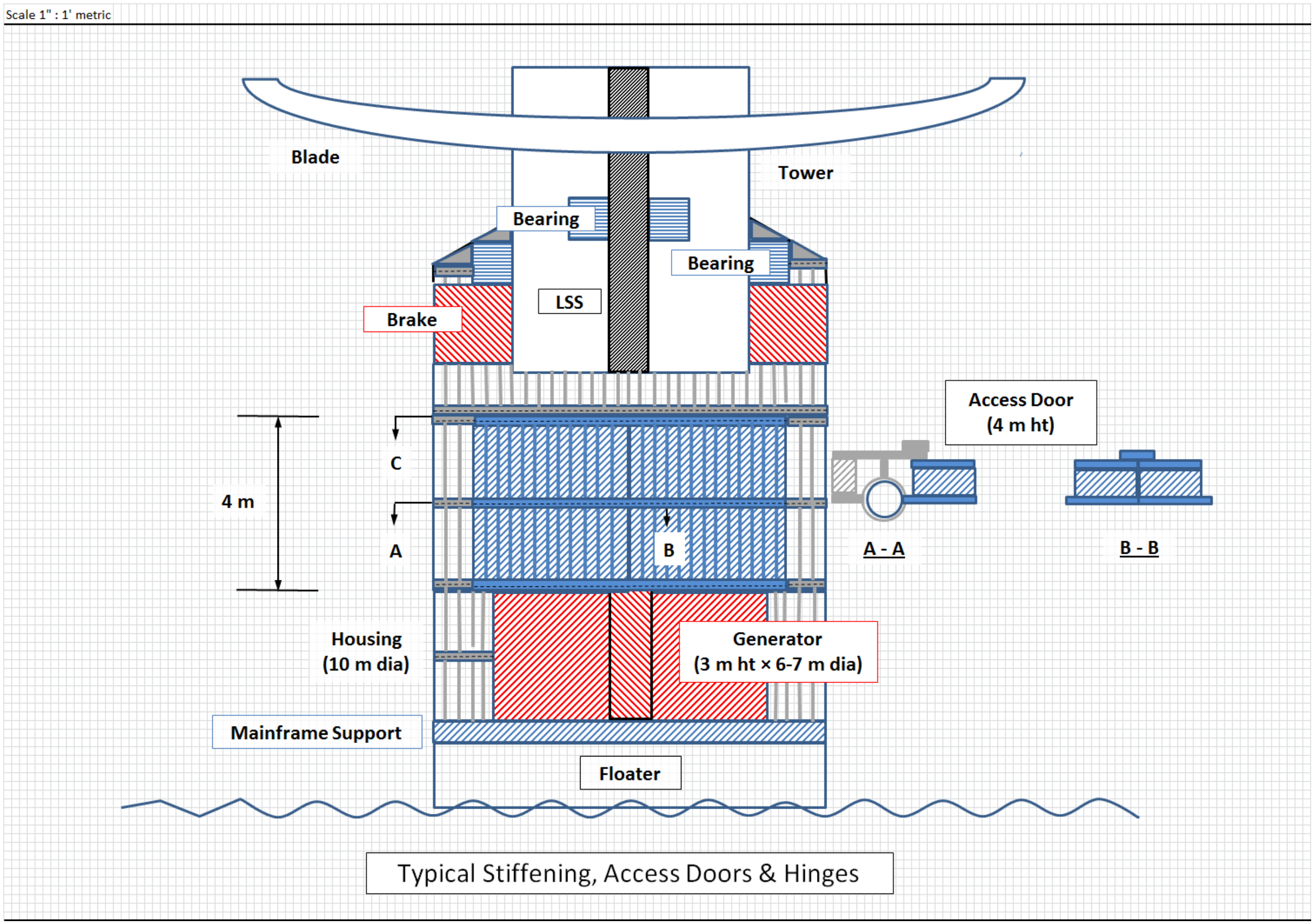


Preliminary Sketch: For Discussion Purposes Only

Logistical Considerations

Generator Removal

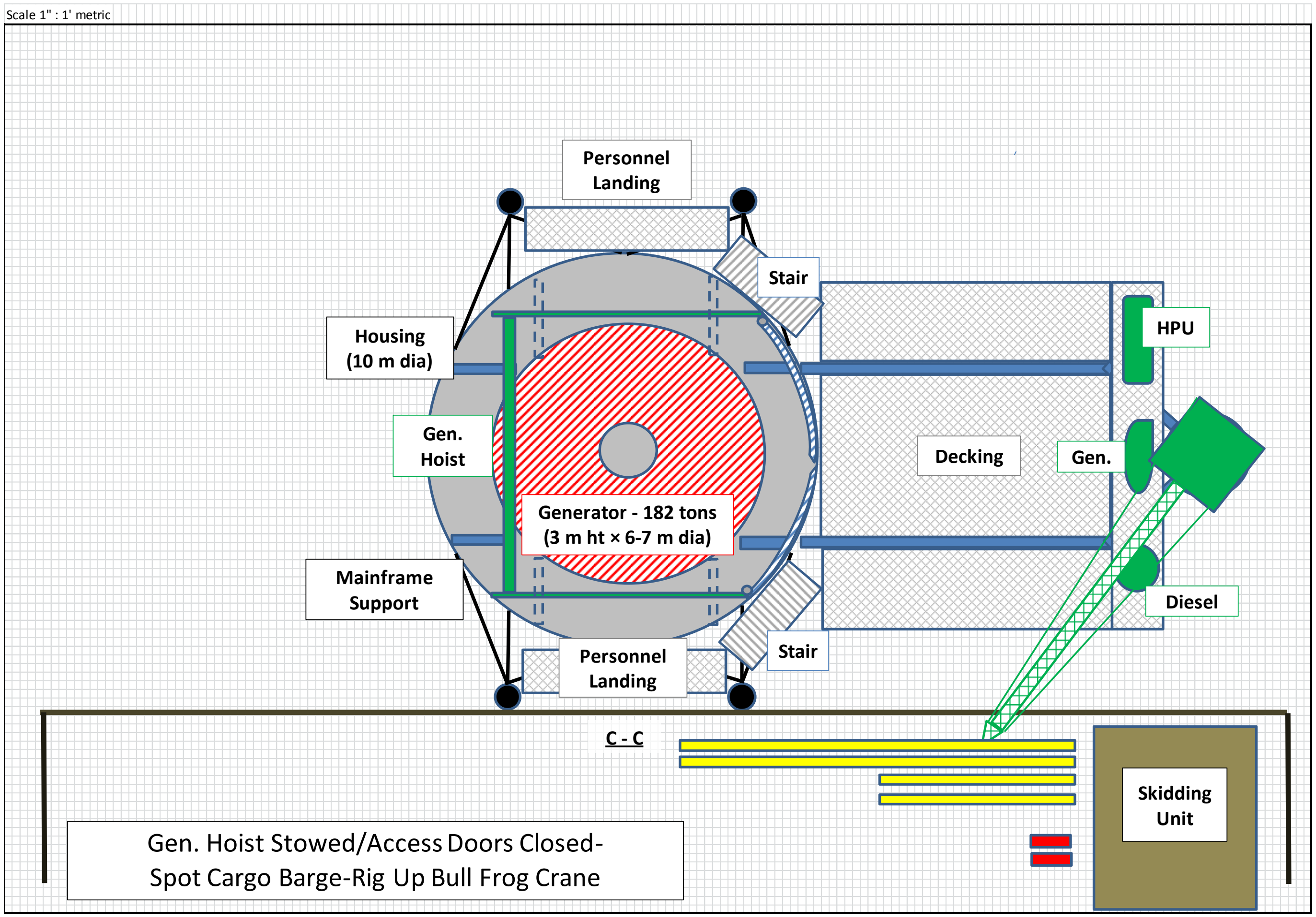
Step C



Logistical Considerations

Generator Removal

Step D

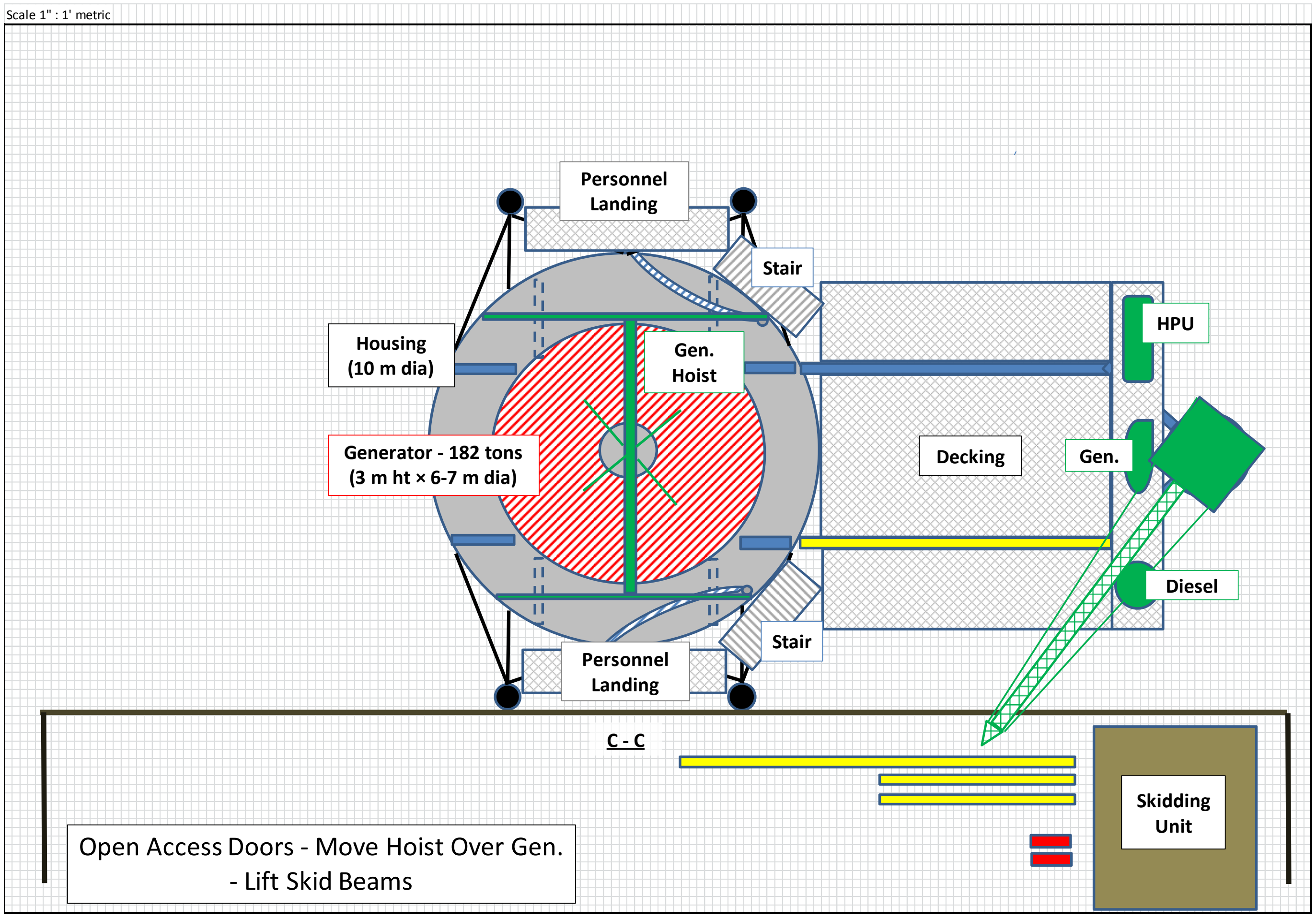


Preliminary Sketch: For Discussion Purposes Only

Logistical Considerations

Generator Removal

Step E



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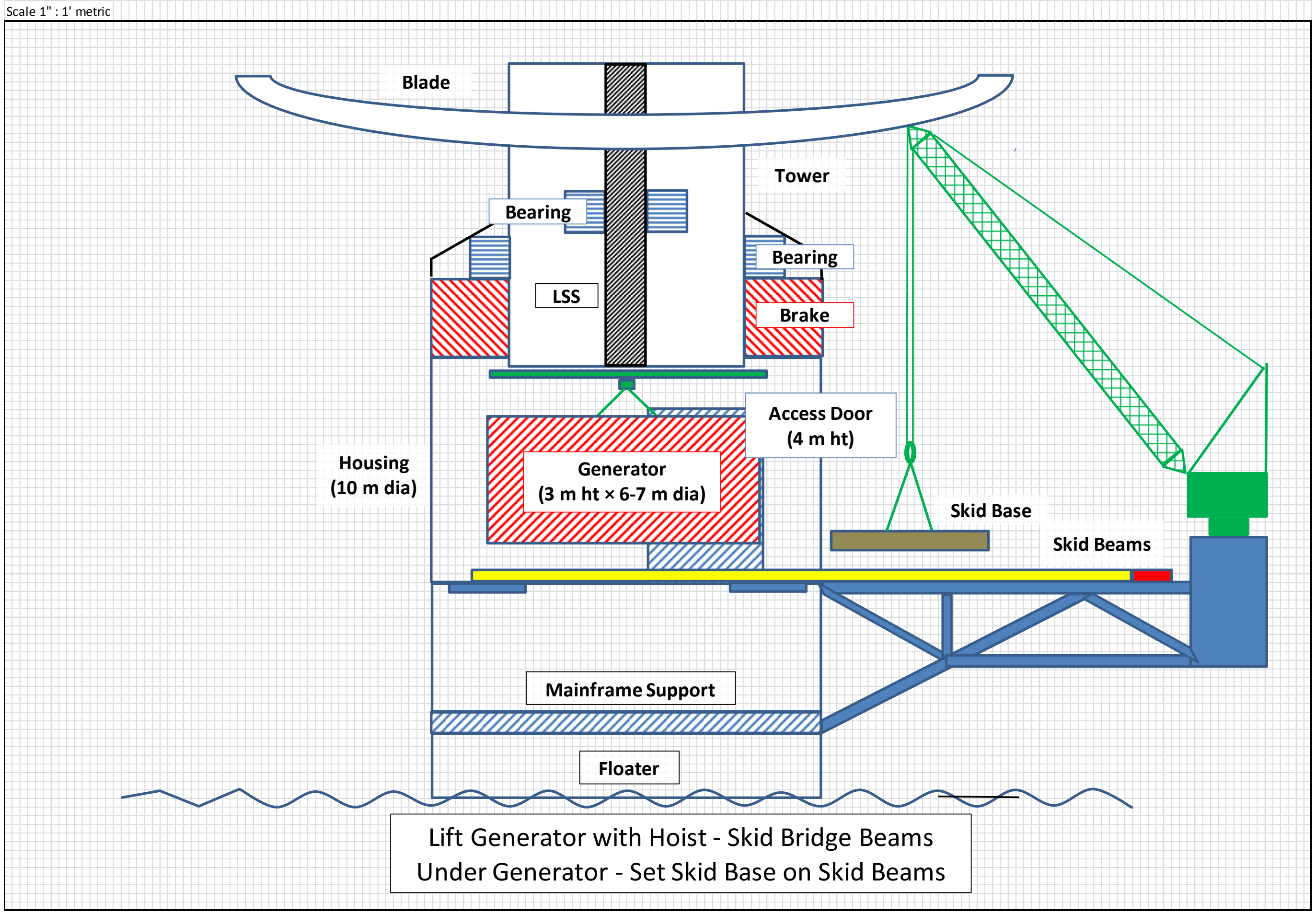
Preliminary Sketch: For Discussion Purposes Only

Logistical Considerations

Generator Removal

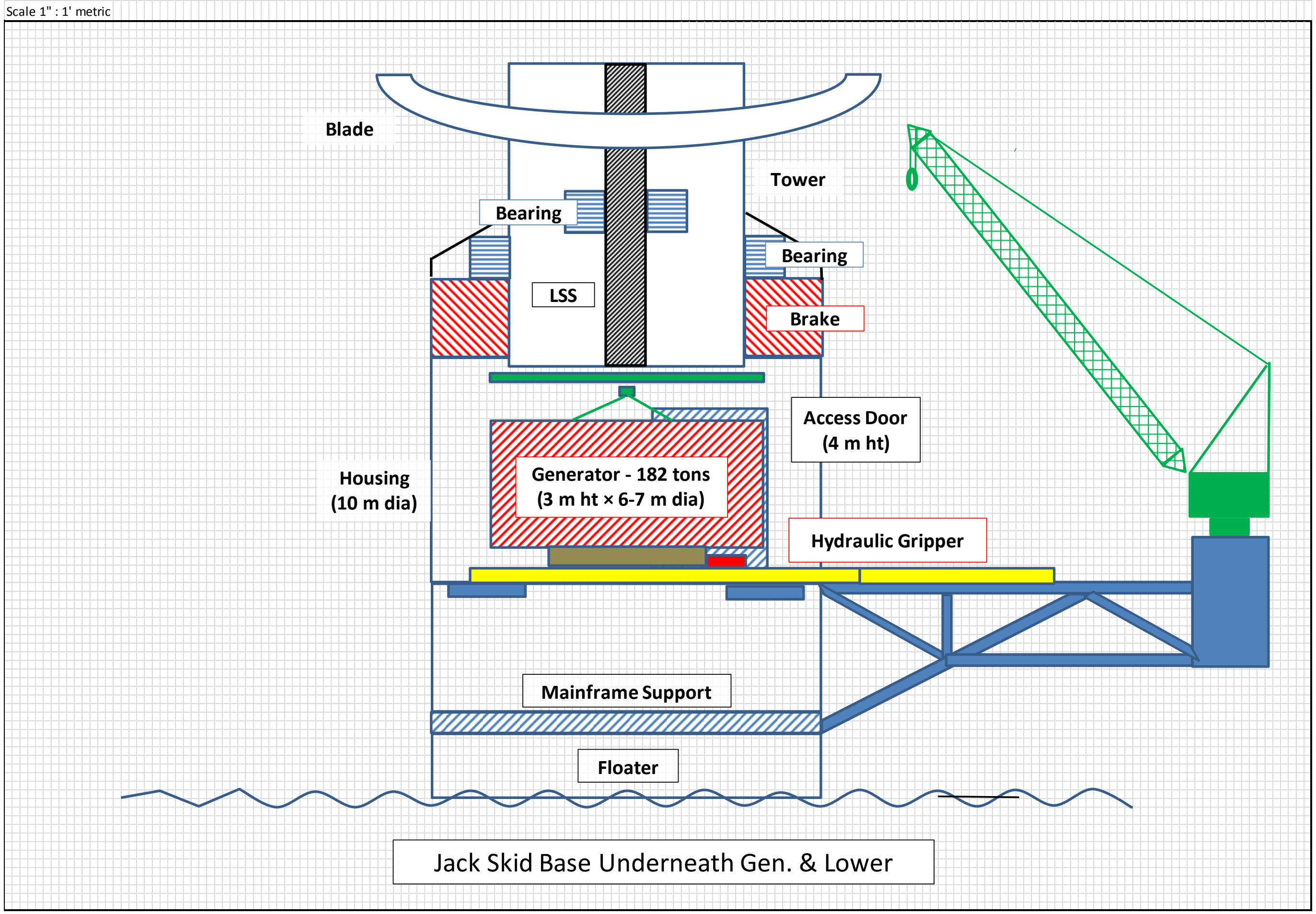
Step F



Logistical Considerations

Generator Removal

Step G

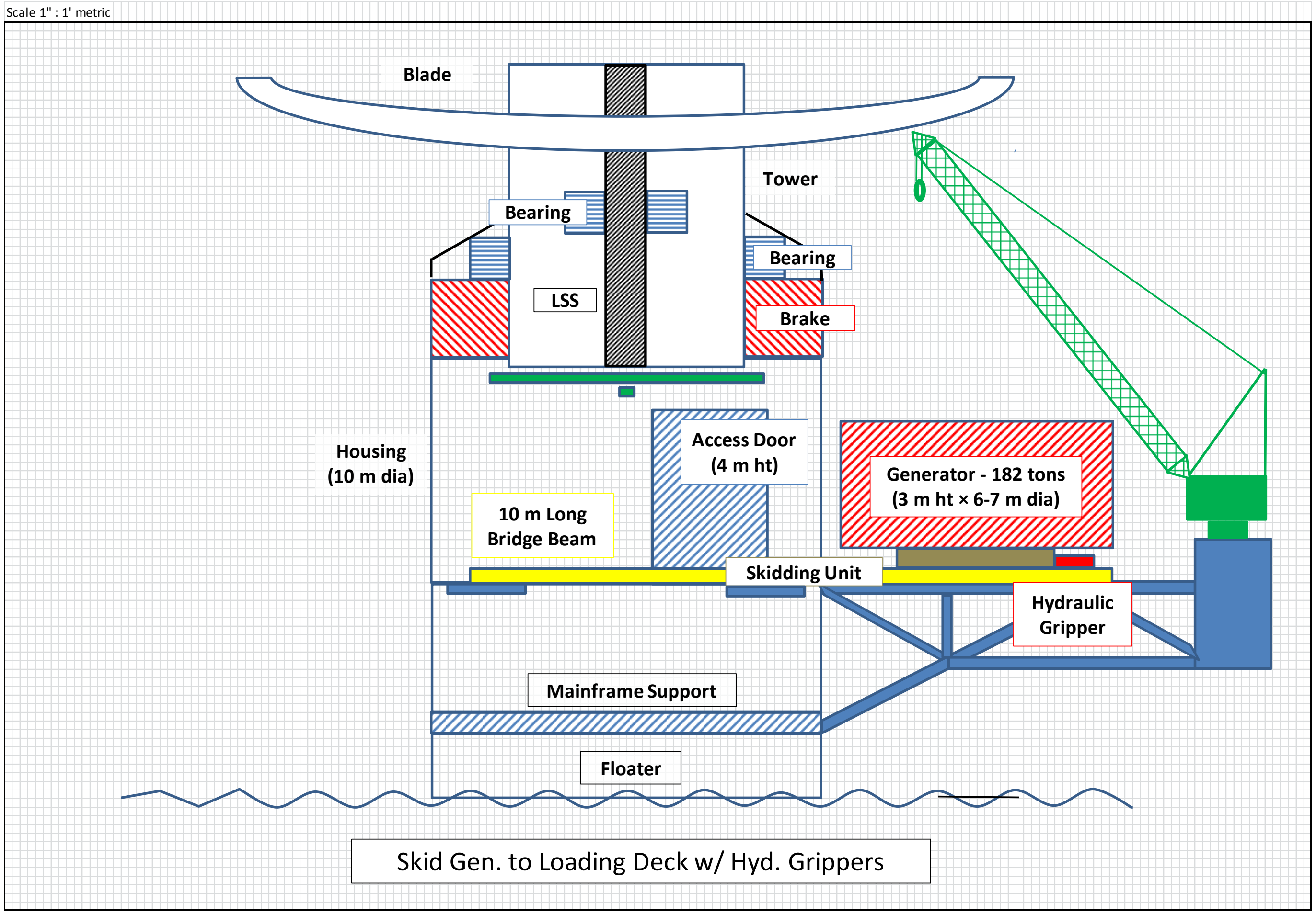


Preliminary Sketche For Discussion Purposes Only

Logistical Considerations

Generator Removal

Step H

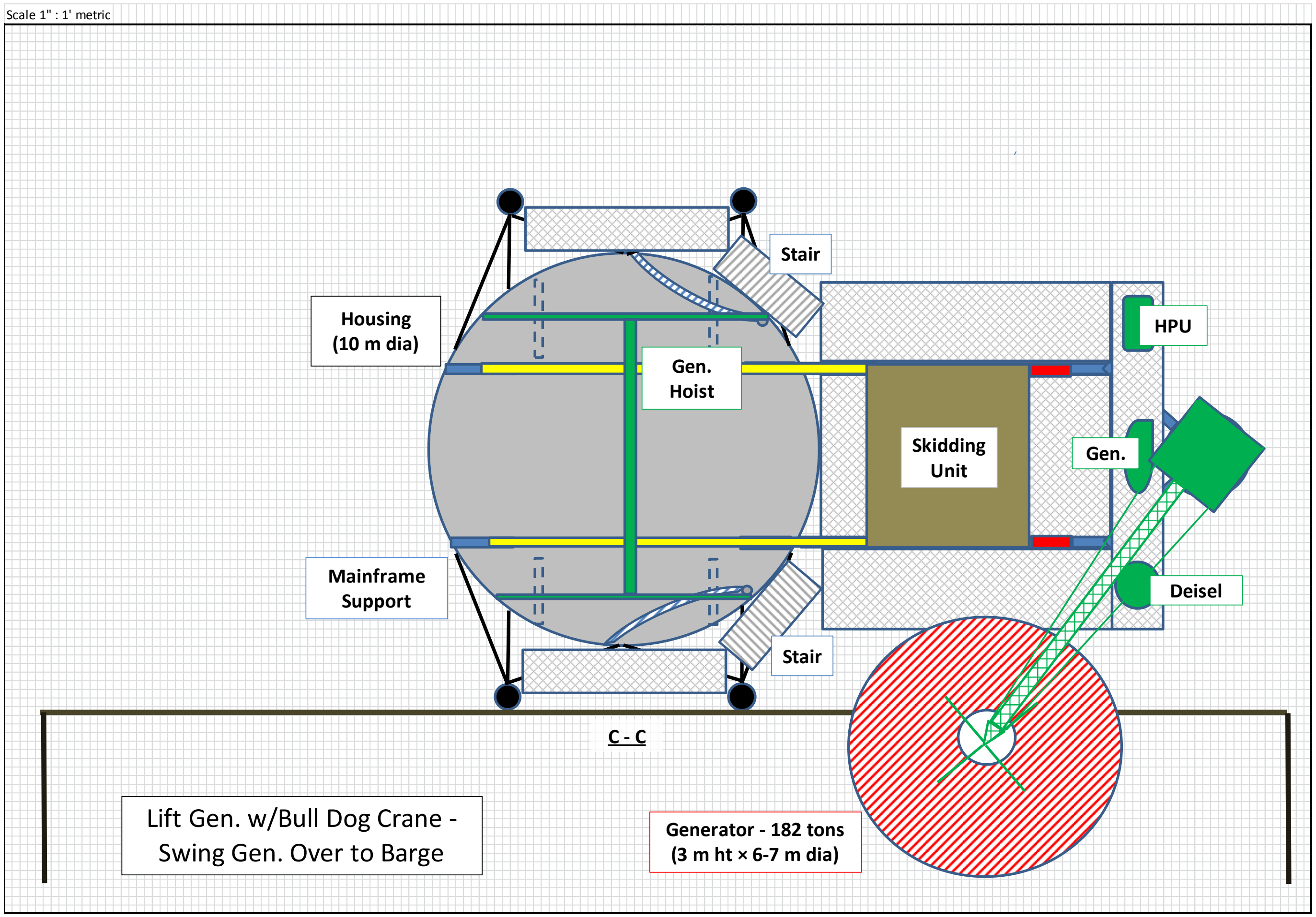


Preliminary Sketch: For Discussion Purposes Only

Logistical Considerations

Generator Removal

Step I



Appendix C

Phase 2 Platform Cost Estimation Details

Phase 2 Cost Estimate for Floating VAWT Hull and Moorings

Date: 28 March 2017

Prepared for: Sandia National Laboratories

Prepared by: Steve Perryman, PE

Review by: John Chappell, PE

Chad Searcy, PhD, PE

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SES Document No.: 1102668-EN-PT-0002 (Rev B)

Basis of Phase 2 Cost Estimate

- Phase 1 Selection of Candidate Hull Form and Mooring Configuration –Wire Rope TLP
- Additional engineering effort included:
  - Updated Turbine Loading Data
  - Spreadsheet Re-Design
  - Application of Historical Weight Density Factors
  - Re-evaluation of Hydrostatics
  - Verification of Stability
  - Calculation of Natural Periods

Basic Assumptions in Phase 2 Cost Estimate

The following reflect differences from the Phase 1 Estimate:

- Efficiency gained from constructing multiple (100) units
  - Although it is not possible to precisely quantify this efficiency, it is prudent to include some benefit since there will certainly be some effect from mass production
- Overhead costs that can be spread over multiple units (100)
  - Engineering and some project management and certification
  - Anchor pile mobilization

Basic Assumptions in Phase 2 Cost Estimate

The range in the costs are intended to reflect:

- Anticipated discounts from the large volume of steel required for the wind farm (> 300,000 tonne)
- Potential savings from the use of typical industry specifications in lieu of customized specifications
- Acknowledgement that the VAWT platforms will typically be un-manned
- Uncertainty of geotechnical parameters
- Offshore construction vessel availability
- Potential use of bridge industry wire rope fittings

Type of Cost Estimate

Type 3 Cost Estimate based on the Cost Estimate Classification System – AACE International RP 17R-97

Estimate Class	Level of Project Definition	End Usage	Expected Accuracy Range	Preparation Effort
5	0 to 2%	Screening or Feasibility	+/- 50%	Minimal
4	1 to 15 %	Feasibility or Concept Study	+/- 35%	
3	10 to 40%	Budgetary or Control	+/- 25%	
2	30 to 70 %	Control or Bid Tender	+/- 15%	
1	50 to 100%	Check Estimate or Bid Tender	+/- 10%	Maximal

- The expected accuracy range of this estimate is ~ +/- 20%

Aspects Included in Cost Estimate

Construction of Hull and Turbine Support Structures

- Materials-Bulks and Equipment
- Fabrication-Labor and Equipment
- Project Management, Overhead and Profit
- Engineering
- Certification

Procurement and Fabrication of Mooring System

- Procurement of Wire Rope and Terminations
- Procurement of Tendon Connectors, Tensioners, Ball Grabs, Buoyancy
- Materials & Fabrication of Suction Piles

Aspects Included in Cost Estimate

Tow Out of Floating Platform and Connection to Moorings

- Installation of Anchor Piles and Lower Tendon Sections
- Tow of Floating Platform to Site with VAWT Installed
- Connection of Upper and Lower Tendons
- Connection of Subsea Transmission Cable
- Ballasting of Platform to Operating Draft
- Removal of Installation Equipment

Aspects Implicit in Cost Estimate

Estimated Percentages for Materials included in the Fabrication Cost

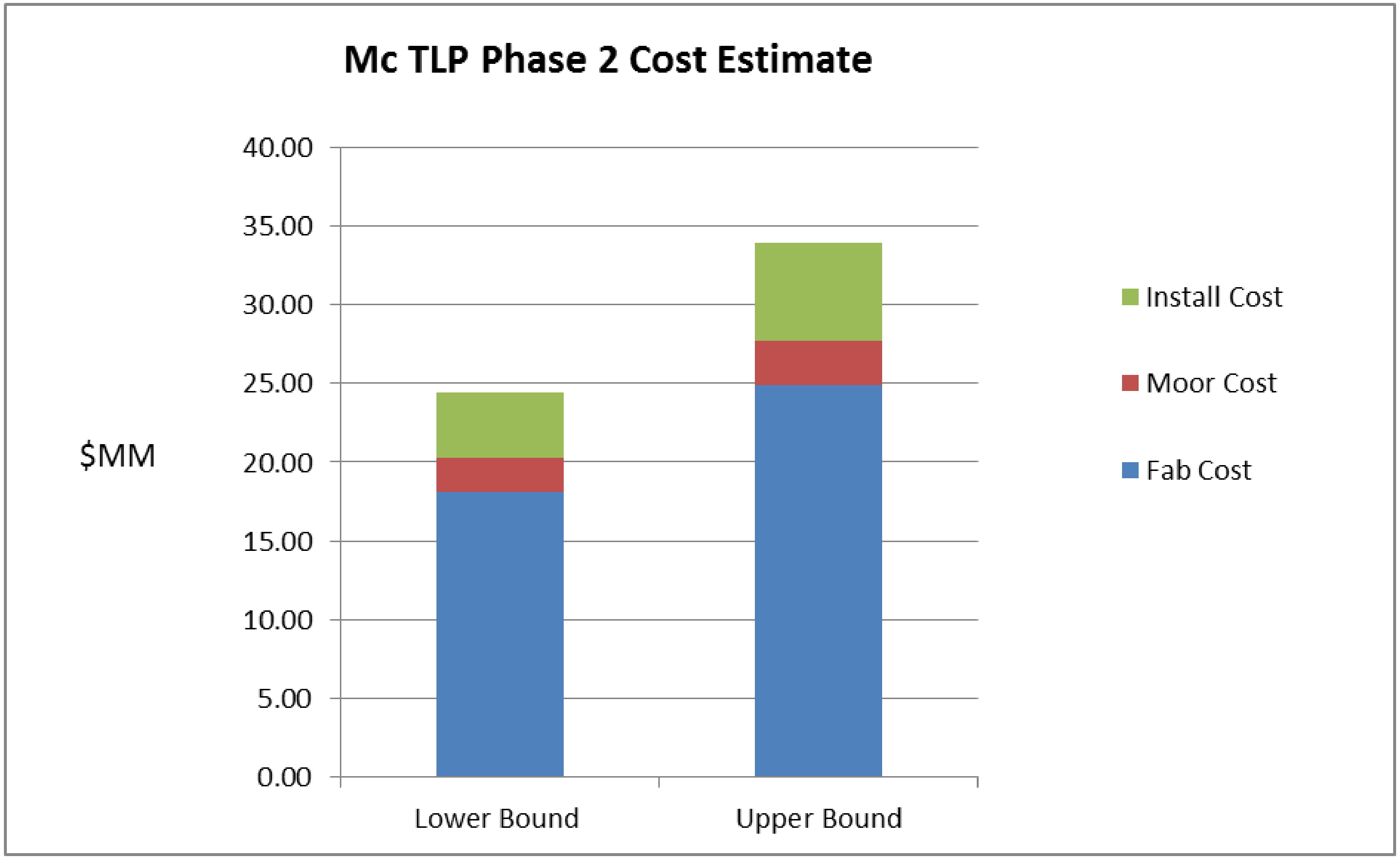
• Mooring Lines	75%-85%
• Anchor Piles	25%-30%
• Cylindrical Cells	20%-25%
• Special Substructures	5%-10%

Note - There are also some costs associated with offloading, handling, storage, disposal (reels), duties, taxes, etc. even for such things as wire rope tendons, which require minimal fabrication.

Aspects not Covered by Cost Estimate

- Costs of Pre-Construction Activities, such as:
  - Contractor(s) Selection
  - Prototype Testing, Licensing and Permitting
  - Preparation of Dry Dock(s)
  - Seafloor Geo-Hazard and Geotechnical Survey
  - Fabrication Method e.g., Crane Requirements
  - Dredging of Towing Channel (if required)
- Laying of Transmission Cable to Wind Farm Site
- Hook-up and Commissioning of Turbine System
- Inflation
- Market Conditions
- Role of US Government (if any)

Offshore VAWT Platform Estimated Cost



- Total Cost Est. per MW $4.89 mm/MW - $6.80 mm/MW

Thank You!

Limitations of This Report

This report is prepared for the sole benefit of the Client, and the scope is limited to matters expressly covered within the text. In preparing this report, Stress Engineering Services, Inc. (SES) has relied on information provided by the Client and, if requested by the Client, third parties. SES may not have made an independent investigation as to the accuracy or completeness of such information unless specifically requested by the Client or otherwise required. Any inaccuracy, omission, or change in the information or circumstances on which this report is based may affect the recommendations, findings, and conclusions expressed in this report. SES has prepared this report in accordance with the standard of care appropriate for competent professionals in the relevant discipline and the generally applicable industry standards. However, SES is not able to direct or control operation or maintenance of the Client's equipment or processes.

Rev	Date	Description	Originator	Reviewer	Approver (Client Name)
B	28-Mar-2017	Issued for Client Review	Steve Perryman	Chad Searcy John Chappell	

Revision	3
Case	Phase 2 - Lower Bound
Installation	150 m WD - Wire Rope TLP
Date	3/24/2017
Prepared	SRP

Item	Sub-Item	No.	Total (MM USD)	Unit of Measurement	Total Quantity	Unit Price (USD)	Item Cost (MM USD)	Notes
Hull			18.092	ton	3,192			
Project Costs			1.966	$/ton		616		Hull & Mooring only
	Project Management							
	Overhead							
	Profit							
	Engineering							Costs spread over 100 units
	Certification							Costs spread over 100 units
	Subtotal			$/ton		616		
Turbine Support Structure			0.950	ton	188	$ 5,052		
	Turbine Structural Interface							Connects turbine housing to hull
	Main Support Beams							Ties tops of columns together
	Secondary Bracing							Interconnects main support beams
	Deck Area							Space for temporary equipment
	Walkways, Handrails and Ladders							Access/Egress
	Subtotal			ton	188			
Interior Columns			3.645	ton	721.5	$ 5,052		
	Top Deck							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Keel Deck							Plate and stiffeners
	Subtotal				578			
	Anodes - External							Corrosion protection
	Manways, Walkways, Handrails and Ladders - Internal							Internal Access
	Subtotal				57.5			
	Shear Plates - Horizontal				17.3			Plates between columns
	Shear Plates - Vertical				69.2			Plates between columns
Outer Columns			11.532	ton	2,283	$ 5,052		
Upper Void Tank								
	Top Deck							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Subtotal			ton	927			
	Manways							Top of column access
	Walkways, Handrails and Ladders - Internal							Internal access
	Vents and Sounding Tubes - Internal							Reqd. by USCG
	Painting for Splash Zone - External							Corrosion protection
	Pneumatic Tubes							Pass through to ballast tank
	Subtotal			ton	93			
	Power Cable Guide - External (Single Column)							Prevents clashing
	Tendon Porches - External							Supports tensioners
	Ladder - External							Access/Egress
	Subtotal			ton	139			
Lower Void Tank								
	Deck - Upper							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Subtotal			ton	449			
	Manways							Lower Void Access
	Walkways, Handrails and Ladders - Internal							Internal access
	Vents and Sounding Tubes							Reqd. by USCG
	Painting for Splash Zone - External							Corrosion protection
	Pneumatic Tubes							Pass through to ballast tank
	Subtotal			ton	45			
	Anodes - External							Corrosion protection
	Barge Fenders - External							Collision protection
	Personnel Transfer Structure - External							Access & Egress from workboat
	Tow Bollards - External							Reqd. for towing
	Power Cable Guide - External (Single Column)							Prevents clashing
	Subtotal			ton	67			
Variable Ballast Tank								
	Deck - Upper							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Keel Deck							Plate and stiffeners
	Subtotal			ton	449			
	Anodes - Internal							Corrosion protection
	Seachest							Allows ingress & egress of seawater ballast
	Pneumatic Tubes							Allows pressure to change ballast
	Subtotal			ton	45			
	Anodes - External							Corrosion protection
	Tow Bollards - External							Connects to tow line
	Bellmouth							Power Cable(Single Column)
	Bellmouths							Tendons
	Subtotal			ton	67			
Hull Equipment								
	Ballast Tank Pressure Monitoring System							Not included
	Tendon Tension Monitoring System							Not included
	Air Compressor							Not included
Tendon System			2.178					
Tendon Assemblies		8	0.915		4068	$ 225	$ 0.915	
	Top Tensioners							Mechanical, manually operated
	Top Connectors							Connect wire rope tendon to tensioner
	Wire Ropes							Upper tendons with fittings
	Spacer Assemblies							Prevents clashing
	Subsea Buoys							Supports lower portion of tendons
	Subsea Connection							ROV operated
	Wire Ropes							Lower tendons
	Bottom Connectors							Connects lower tendon to ball grab
	Ball Grabs							Connects tendon to foundation
	Subtotal			ft	4068	$ 225	$ 0.915	
Templates/Piles		8	1.263		400	$ 3,157	$ 1.263	
Foundation Templates								
	Structural Framing							Mounted to pile top
	Ball Grab Receptacles							Connects foundation to tendon
	Anodes							Corrosion protection
Piles								
	Suction Valves							ROV operated
	Steel Suction Piles							Provides resistance to tendon tension
	Subtotal			ton	400	$ 3,157	$ 1.263	

Item	Sub-Item	Days	Total (MM USD)	Mobilization (USD)	Fuel/Day (USD)	Day Rate (USD)	Item Cost (MM USD)	Notes
Installation			4.184					
	Anchor Handling Vessel with ROV	3		3,200		$ 160,000	0.483	Install anchor piles spread over 100 units
	3 Ocean Tugs (2 in front, 1 trail)	2		480,000	32,800	$ 240,000	1.026	Tow of hull to site
	Anchor Handling Vessel	2				$ 160,000	$ 0.320	Connection of hull to piles
	3 Ocean Tugs (2 in front, 1 trail)	2			32,800	$ 240,000	$ 0.546	Connection of hull to piles
	Anchor Handling Vessel w/ROV	1				$ 160,000	$ 0.160	Connect Power Cable
	Anchor Handling Vessel	1				$ 160,000	$ 0.160	Ballast hull to set tensions
	Anchor Handling Vessel	1				$ 160,000	$ 0.160	Remove hull equipment
	Anchor Handling Vessel	1		320000		$ 160,000	$ 0.480	Start up VAWT & De-mob AHV
							$ 0.150	Harbor movements
	Subtotal	13				$ 40,000	$ 0.520	Crews & equipment
							$ 0.180	Work, messenger wires, attachments
Grand Total			24.454					

Revision	3
Case	Phase 2 - Upper Bound
Installation	150 m WD - Wire Rope TLP
Date	3/24/2017
Prepared	SRP

Item	Sub-Item	No.	Total (MM USD)	Unit of Measurement	Total Quantity	Unit Price (USD)	Item Cost (MM USD)	Notes
Hull			**24.887**	**ton**	**3,192**			
Project Costs			2.704	$/ton		847		Hull & Mooring only
	Project Managemen							
	Overhead							
	Profit							
	Engineering							Costs spread over 100 units
	Certification							Costs spread over 100 units
	Subtotal			$/ton		847		
Turbine Support Structure			1.307	ton	188	$ 6,950		
	Turbine Structural Interface							Connects turbine housing to hull
	Main Support Beams							Ties tops of columns together
	Secondary Bracing							Interconnects main support beams
	Deck Area							Space for temporary equipment
	Walkways, Handrails and Ladders							Access/Egress
	Subtotal			ton	188			
Interior Columns			5.014	ton	721.5	$ 6,950		
	Top Deck							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Keel Deck							Plate and stiffeners
	Subtotal				578			
	Anodes - Externa							Corrosion protection
	Manways, Walkways, Handrails and Ladders - Interna							Internal Access
	Subtotal				57.5			
	Shear Plates - Horizonta				17.3			Plates between columns
	Shear Plates - Vertical				69.2			Plates between columns
Outer Columns			15.863	ton	2,283	$ 6,950		
Upper Void Tank								
	Top Deck							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Subtotal			ton	927			
	Manways							Top of column access
	Walkways, Handrails and Ladders - Interna							Internal access
	Vents and Sounding Tubes - Interna							Reqd. by USCG
	Painting for Splash Zone - Externa							Corrosion protection
	Pneumatic Tubes							Pass through to ballast tank
	Subtotal			ton	93			
	Power Cable Guide - External (Single Column							Prevents clashing
	Tendon Porches - Externa							Supports tensioners
	Ladder - Externa							Access/Egress
	Subtotal			ton	139			
Lower Void Tank								
	Deck - Upper							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Subtotal			ton	449			
	Manways							Lower Void Access
	Walkways, Handrails and Ladders - Interna							Internal access
	Vents and Sounding Tubes							Reqd. by USCG
	Painting for Splash Zone - Externa							Corrosion protection
	Pneumatic Tubes							Pass through to ballast tank
	Subtotal			ton	45			
	Anodes - Externa							Corrosion protection
	Barge Fenders - Externa							Collision protection
	Personnel Transfer Structure - Externa							Access & Egress from workboat
	Tow Bollards - Externa							Reqd. for towing
	Power Cable Guide - External (Single Column							Prevents clashing
	Subtotal			ton	67			
Variable Ballast Tank								
	Deck - Upper							Plate and stiffeners
	Shell and Scantlings							Plate and circumferential tee secs.
	Keel Deck							Plate and stiffeners
	Subtotal			ton	449			
	Anodes - Interna							Corrosion protection
	Seachest							Allows ingress & egress of seawater ballast
	Pneumatic Tubes							Allows pressure to change ballast
	Subtotal			ton	45			
	Anodes - Externa							Corrosion protection
	Tow Bollards - Externa							Connects to tow line
	Bellmouth							Power Cable(Single Column)
	Bellmouths							Tendons
	Subtotal			ton	67			
Hull Equipment								
	Ballast Tank Pressure Monitoring Systen							Not included
	Tendon Tension Monitoring System							Not included
	Air Compressor							Not included
Tendon System			**2.855**					
Tendon Assemblies		8	1.119		4068	$ 275	$ 1.119	
	Top Tensioners							Mechanical, manually operated
	Top Connectors							Connect wire rope tendon to tensioner
	Wire Ropes							Upper tendons with fittings
	Spacer Assemblies							Prevents clashing
	Subsea Buoys							Supports lower portion of tendons
	Subsea Connectior							ROV operated
	Wire Ropes							Lower tendons
	Bottom Connectors							Connects lower tendon to ball grab
	Ball Grabs							Connects tendon to foundation
	Subtotal			ft	4068	$ 275	$ 1.119	
Templates/Piles		8	1.736		400	$ 4,341	$ 1.736	
Foundation Templates								
	Structural Framing							Mounted to pile top
	Ball Grab Receptacles							Connects foundation to tendon
	Anodes							Corrosion protection
Piles								
	Suction Valves							ROV operated
	Steel Suction Piles							Provides resistance to tendon tension
	Subtotal			ton	400	$ 4,341	$ 1.736	
Item	**Sub-Item**	**Days**	**Total (MM USD)**	**Mobilization (USD)**	**Fuel/Day (USD)**	**Day Rate (USD)**	**Item Cost (MM USD)**	**Notes**
Installation			**6.276**					
	Anchor Handling Vessel with ROV	3		4,800		$ 240,000	0.725	Install anchor piles spread over 100 units
	3 Ocean Tugs (2 in front, 1 trail)	2		720,000	49,200	$ 360,000	1.538	Tow of hull to site
	Anchor Handling Vesse	2				$ 240,000	$ 0.480	Connection of hull to piles
	3 Ocean Tugs (2 in front, 1 trail)	2			49,200	$ 360,000	$ 0.818	Connection of hull to piles
	Anchor Handling Vessel w/ROV	1				$ 240,000	$ 0.240	Connect Power Cable
	Anchor Handling Vessel	1				$ 240,000	$ 0.240	Ballast hull to set tensions
	Anchor Handling Vesse	1				$ 240,000	$ 0.240	Remove hull equipment
	Anchor Handling Vesse	1		480000		$ 240,000	$ 0.720	Start up VAWT & De-mob AHV
							$ 0.224	Harbor movements
	Subtotal	13				$ 60,000	$ 0.780	Crews & equipment
							$ 0.270	Work, messenger wires, attachments
Grand Total			**34.018**					

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