D10.02 Report – Final Report

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Acronyms and Abbreviations

ABS	American Bureau of Shipping
AC	Alternating Current
EOC	Exmar Offshore Company
ft	Feet
GHS	General Hysrostatics
H_s	Significant Wave Height
HP	Horsepower
in	Inch
kN	KiloNewton
kips	Kilopounds
lb	Pounds
N	Newton
m	Meter
mm	Millimeter
MOU	Mobile Offshore Unit
MODU	Mobile Offshore Drilling Unit
MT	Metric Tonne
MW	Megawatts
NOWRDC	National Offshore Wind Research and Development Consortium
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
RPM	Revolutions Per Minute
S	Seconds
STBD	Starboard
T_p	Wave Period
V	Velocity
WTIV	Wind Turbine Installation Vessel

1 Introduction

1.1 Project Background/Objectives

Offshore wind turbines require a stable (fixed) work platform or vessel with heavy duty, extended reach lift capability for the installation of the turbine components. The vessels required for future East Coast U.S. wind development will require lifting capability up to and including 15 MW to handle the latest and future sizes of turbines being manufactured. Existing installation vessels are non-Jones Act compliant and therefore unable to enter U.S. ports to receive turbine components. In response to this situation, Dominion Energy of Virginia is heading an unnamed consortium of offshore wind industry players and has contracted Keppel AmFELS to build the first Jones Act compliant WTIV at its shipyard in Brownsville, Texas. The cost for the WTIV was reported to be in excess of $500 million. Additionally, the WTIV, named Charybdis, has been chartered to Ørsted and Eversource for the construction of two offshore wind farms at the Revolution Wind and Sunrise Wind developments and will operate out of New London, Connecticut.

The Contractor’s concept utilizes two existing mobile offshore drilling jack-ups which were built in the United States. The two units will be mated into one vessel with an appropriately sized mid-body section built in a US fabrication facility or shipyard. The single assembled vessel will be referred to as the Wind Turbine Installation Vessel, or “WTIV”. The vessel will be refurbished for life extension and outfitted with equipment for efficient transport, installation, and commissioning of foundations and turbines, The resulting wind turbine installation vessel will be re-flagged in the U.S. and will be Jones Act compliant. The anticipated cost for this concept will be one-third to one-half the cost of a new vessel built in the U.S. based on preliminary Contractor estimates. This Study will assess the technical and commercial feasibility of the concept as a potential solution to the challenges facing us offshore wind developers.

1.2 Objective Statement

This document serves as the Final Report for this work.

$744 of Cost Sharing has been applied to the creation of this deliverable.

1.3 Work Scope

The Final Report serves to summarize all aspects of the work performed as part of the project. This includes overall review of the work performed, as well as discussions of the observations and findings and recommendations, if any, from all tasks, and avenues for further improvements, as appropriate.

2 Project Overview

2.1 Project Phases and Tasks

The project was divided into three Phases with “go/no-go” gates at the end of Phases 1 and 2, with an overall original duration of roughly one year. The Phases were as follows:

- Phase 1 – Preliminary Assessments
- Phase 2 – Naval Architecture Finalization
- Phase 3 – Concept Completion

2.1.1 Phase 1

The first phase of work began the design cycle for the WTIV conversion concept specifically for the base turbine design (NREL 15 MW). Tasks for this phase included the following:

- Preliminary Basis of Design development (Draft version; finalized at the end of the project)
- General Arrangement drawings and midbody scantlings drawings (hull connection section)
- Material handling study of the loading, storage, and installation of wind turbine components
- Lightship estimate and variable load condition development for specified load cases
- Preliminary motions assessment

2.1.2 Phase 2

The second phase focused on completion of those tasks started in Phase 1 through a second design cycle to adjust and finalize concept details. Tasks for this phase included the following:

- Set final layouts and arrangements for the WTIV and wind turbine components
    - General Arrangement drawings
    - Material handling sequence drawings
    - Midbody scantlings and MTO
- Finalize lightship estimate and preliminary loading conditions / stability check
- Finalize motions assessment
- Begin development of the longitudinal strength assessment

2.1.3 Phase 3

The third phase included finalization of structural assessments and completion of remaining concept details. Tasks for this phase included the following:

- Finalize longitudinal strength assessment
- Perform preliminary assessment of WTIV drag and power requirements
- Perform preliminary jacking system assessment to understand jacking requirements for the WTIV
- Develop cost estimate
- Finalize Basis of Design document based on project findings
- Develop Final Report and close out project

2.2 Preliminary Concept Development

Prior to the start of the project, some basic concept design work had been completed to begin the concept validation process. The general conversion concept was envisioned as follows:

- Acquire two LeTourneau Model 116C US built jack up MODUs
- Remove cantilevers, drilling packages, and all other unnecessary equipment (e.g. mud system)
- Remove Living Quarters and helideck module from one unit
- Build a hull section (or "midbody") to connect the units
- Upgrade jacking system and controls
- Re-power the vessel, as required
- Integrate the hulls with the midbody
- Install the heavy lift crane
- Add the dynamic positions thruster system
- Add the personnel transfer tower

A simple, step-by-step illustration of the conversion process is outlined in Figure 1, with a 3D rendering of the preliminary WTIV concept is presented in Figure 2, and associated deck layout in Figure 3 and Figure 4. The preliminary concept considered turbines up to 10 MW in size and was based on principal particulars as shown in Table 1.

Figure 1. Preliminary WTIV Concept Conversion Process.

A step-by-step illustration of the preliminary WTIV conversion process.

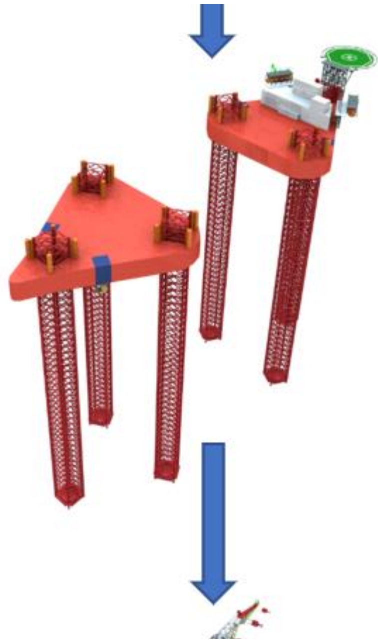


Figure 2. Preliminary WTIV Concept 3D Rendering.

3D rendering of the preliminary WTIV concept developed prior to the start of the project.

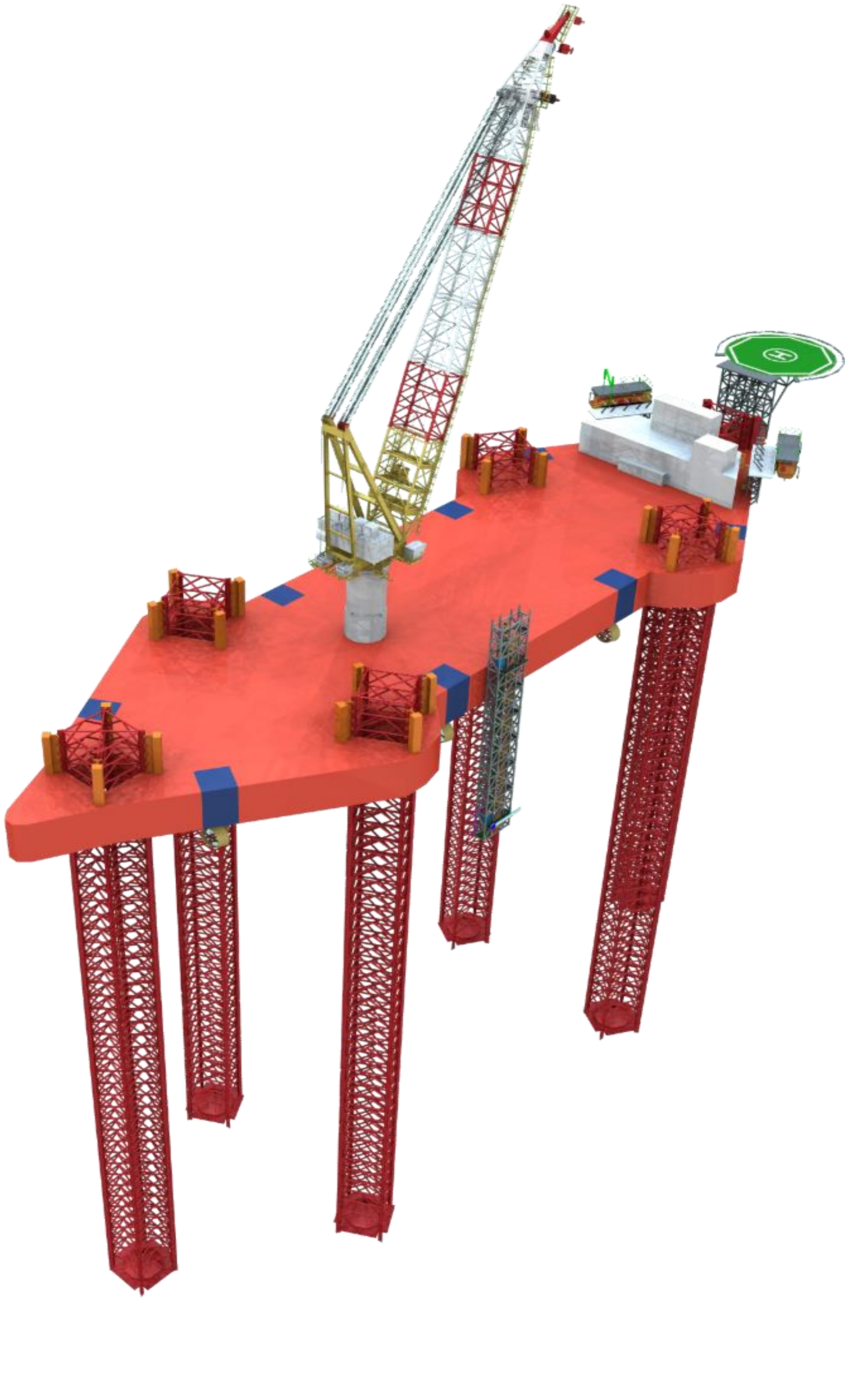


Figure 3. Preliminary WTIV Concept Deck Layout – Plan View.

Deck layout drawing of the preliminary WTIV concept developed prior to the start of the project.

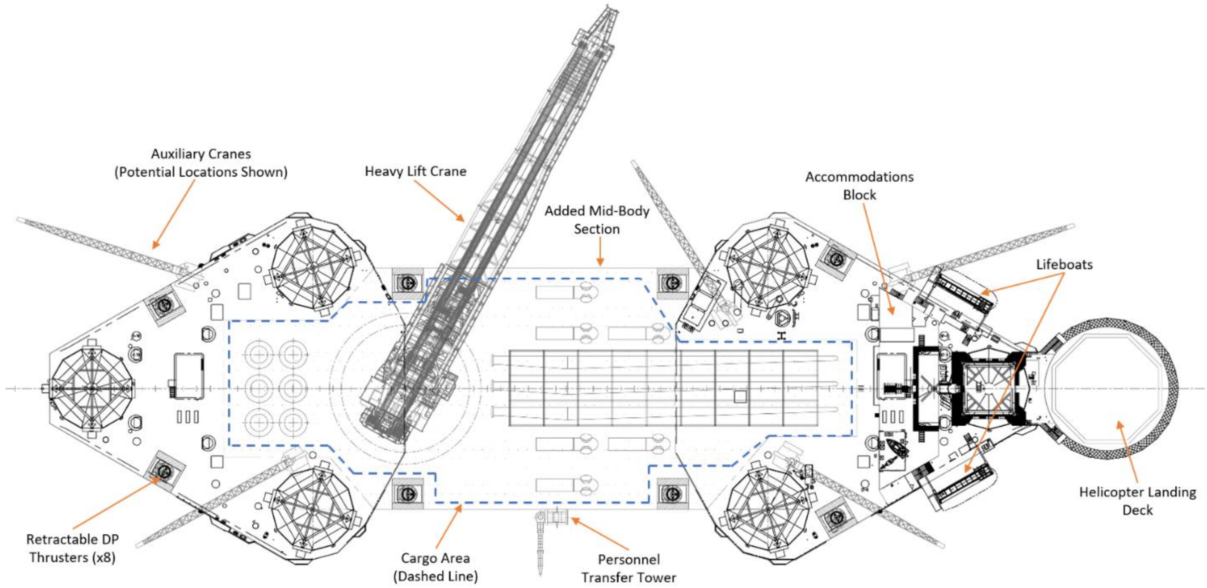


Figure 4. Preliminary WTIV Concept Deck Layout – Elevation View.

Deck layout drawing of the preliminary WTIV concept developed prior to the start of the project.

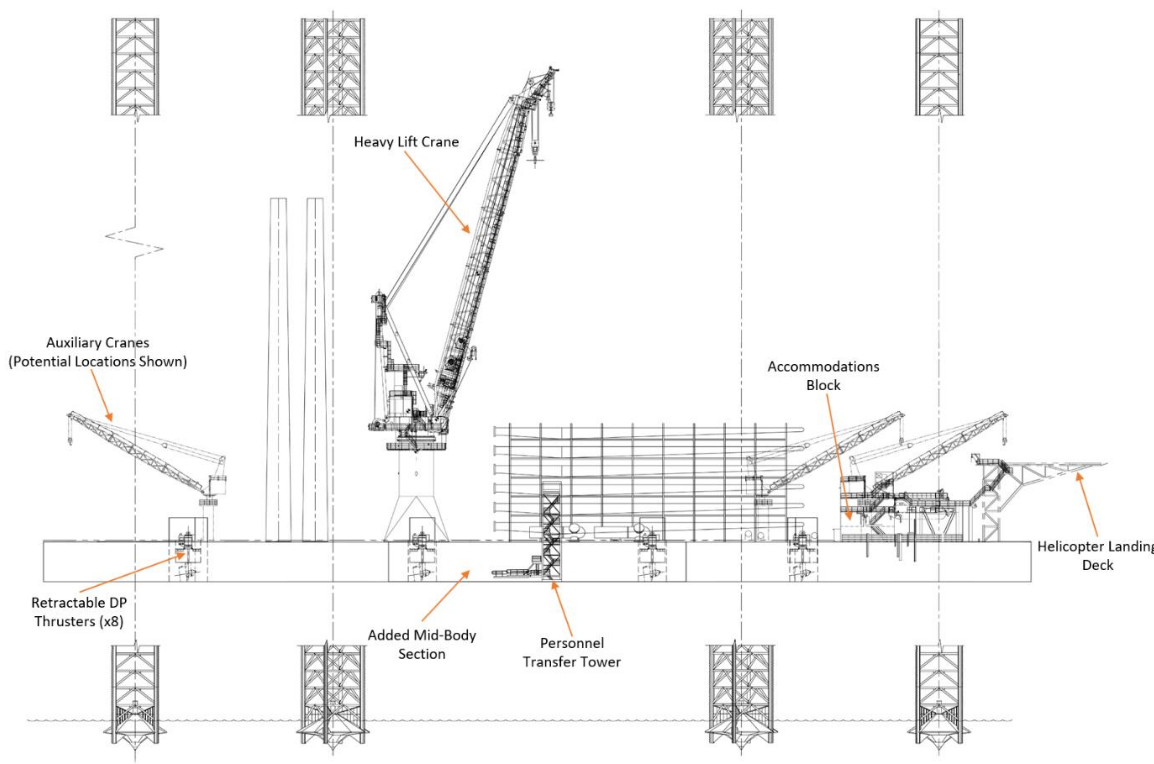


Table 1. Preliminary WTIV Concept – Principal Particulars.

Principal particulars for the preliminary WTIV concepts including dimensions, speeds, and regulatory information.

Principal Particulars	
Length Overall (Including Heliport)	211.7 m
Length Between Perpendiculars	196.3 m
Breadth	61.1 m
Depth	7.9 m
Draft (Design)	4.3 m
Draft (Max)	4.9 m
Elevated Payload	4,082 tonnes
Maximum Speed	8 – 10 knots
Leg Length	145.5 m
Maximum Leg Protrusion	122 m below Bottom of Hull
Class	ABS
Flag	USA

3 Phase 1 Developments

Phase 1 tasks, termed "Preliminary Assessments", focused on the first major pass through the design cycle for the WTIV conversion concept specifically considering the NREL 15 MW turbine as the baseline. Details of the individual tasks are expanded upon in the following subsections.

3.1 Preliminary Basis of Design

A Draft version of the Basis of Design for the concept was developed as a guideline document for the work. This was considered as a "fluid" document to be updated and augmented as necessary throughout the project, concluding with a finalized Basis of Design at the end of the work that provides the most accurate details for the concept upon project conclusion (done as part of Phase 3). This document was titled "D01.01 Memorandum – Basis of Design (DRAFT)".

3.2 Preliminary General Arrangements, Midbody Scantlings, and Material Handling Study

The main focus of the early design work centered on identifying the optimal deck layout for the WTIV in order to efficiently handle the target turbine. This was an iterative process considering the overall lightship of the vessel, the cargo capacity, and jacking capacity. Finding a suitable ratio of midbody size to cargo weight was at the heart of the process, which was informed by material handling study considerations to guide the cargo layout options.

Discussions were held with Advisory Board member Cees Van Veluw of Huisman that provided valuable insight into the material handling and options for better arrangements of the turbine components to maximize use of space and foresee installation benefits.

The following figures (i.e. Figure 5, Figure 6, and Figure 7) provide a view of the initial three main layouts that were considered. Options 1 and 2 were challenged by the large midbody section and issues of lightship vs. cargo capacity. Option 3 offered better lightship vs. cargo capacity; however the asymmetric nature of the crane and cargo storage provided challenges of its own. The perpendicular nature of the blades relative to the crane offered better blade handling characteristics compared to Options 1 and 2. At that stage it was expected that some iteration of Option 3 would provide the most advantageous combination of cargo capacity and operational versatility.

Figure 5. Plan View – WTIV General Arrangement Option 1.

Plan view of Option 1 for the WTIV illustrating the deck layout and general concept as developed in Phase 1 of the project.

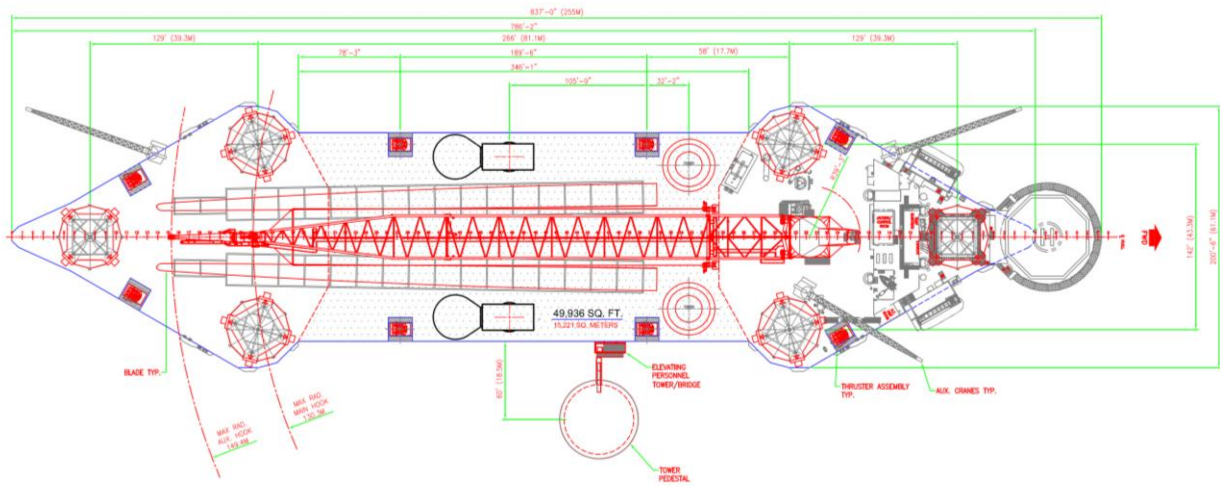


Figure 6. Plan View – WTIV General Arrangement Option 2.

Plan view of Option 2 for the WTIV illustrating the deck layout and general concept as developed in Phase 1 of the project (reverse equipment orientation compared to Option 1).

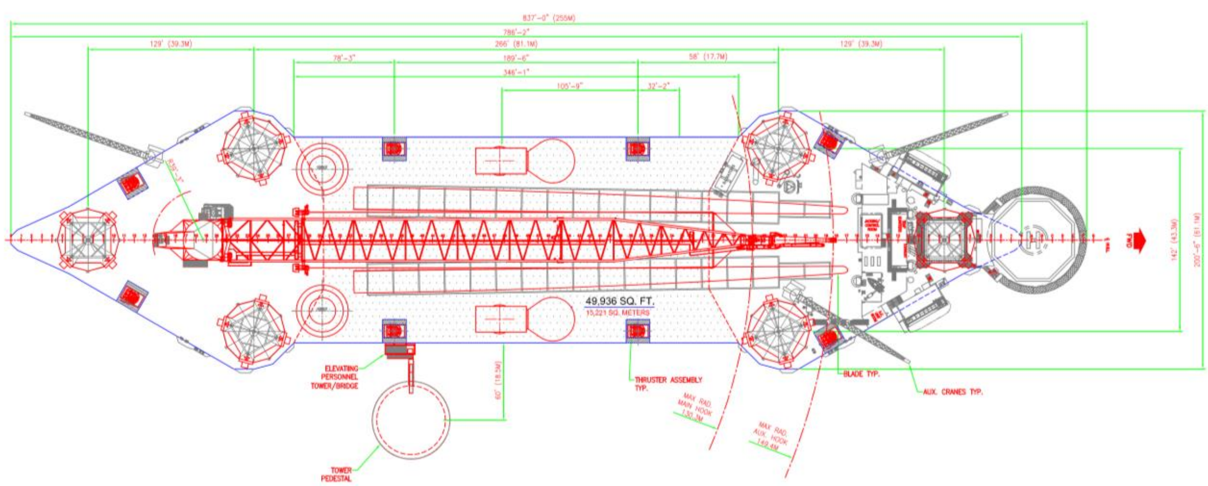
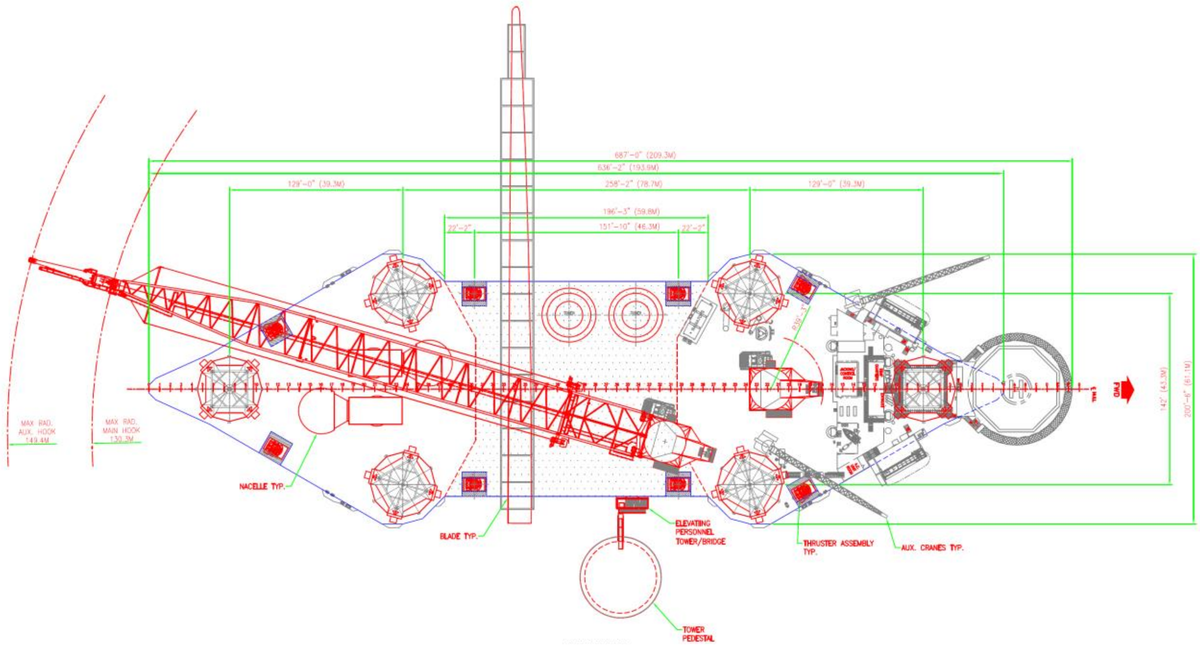


Figure 7. Plan View – WTIV General Arrangement Option 3.

Plan view of Option 3 for the WTIV illustrating the deck layout and general concept as developed in Phase 1 of the project (blade storage rotated 90 degrees and crane shift to minimize midbody length).



Based on this “Option 3” layout, two final layout candidates emerged: the “wing deck” and “full depth” midbody section options. Both offered the same footprint and cargo area and were virtually identical in the plan view. The main difference was the potential for reduced steel weight in the wing deck option for the new midbody. Both options were vetted through the material handling sequence drawing development to ensure adequate spacing existed to allow for proper handling of the turbine components during loading and installation operations. The wing deck layout option was utilized to develop the draft version of the load conditions evaluation and preliminary motions assessment based on the consideration that weight savings would be necessary in the midbody.

The following figures provide views of the “wing deck” and “full depth” midbody options. Figure 8 shows the plan view of the wing deck midbody option, while Figure 10 shows the full depth midbody option. Both are virtually identical in terms of their deck. The full depth midbody option allowed for the addition of an 8th thruster to assist in WTIV powering. This is based on the deeper hull section allowing for use of a non-retractable thruster, which will not require a structure atop the deck to house the retracted structure (which is the case for the midbody thrusters on the wing deck option). Figure 9 depicts the section shape of the wing deck midbody, while Figure 11 depicts the section shape of the full depth midbody. These views were captured in the Documents titled “D02.01 General Arrangement – Plan View (DRAFT)” and “D02.02 General Arrangement – Elevation View (DRAFT)”.

Figure 8. Plan View – WTIV General Arrangement – Wing Deck Midbody.

Plan view of the Wing Deck Midbody option for the WTIV illustrating the deck layout and general concept as developed in Phase 1 of the project.

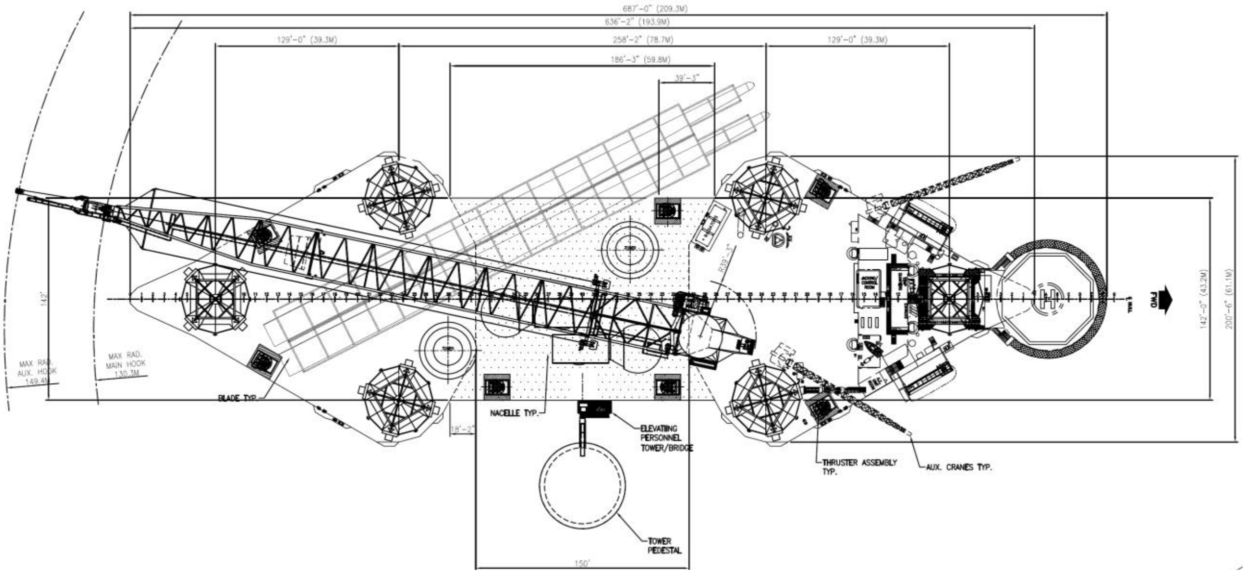


Figure 9. Section View - WTIV Wing Deck Midbody.

Section view of the Wing Deck Midbody option for the WTIV as developed in Phase 1 of the project.

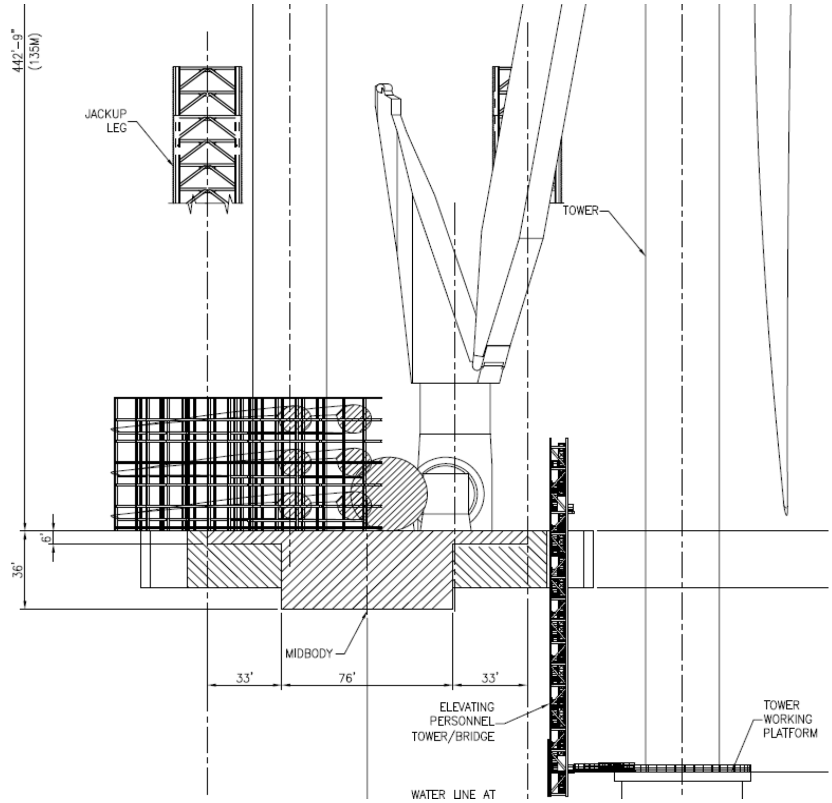


Figure 10. Plan View - WTIV General Arrangement – Full Depth Midbody.

Plan view of the Full Depth Midbody option for the WTIV illustrating the deck layout and general concept as developed in Phase 1 of the project.

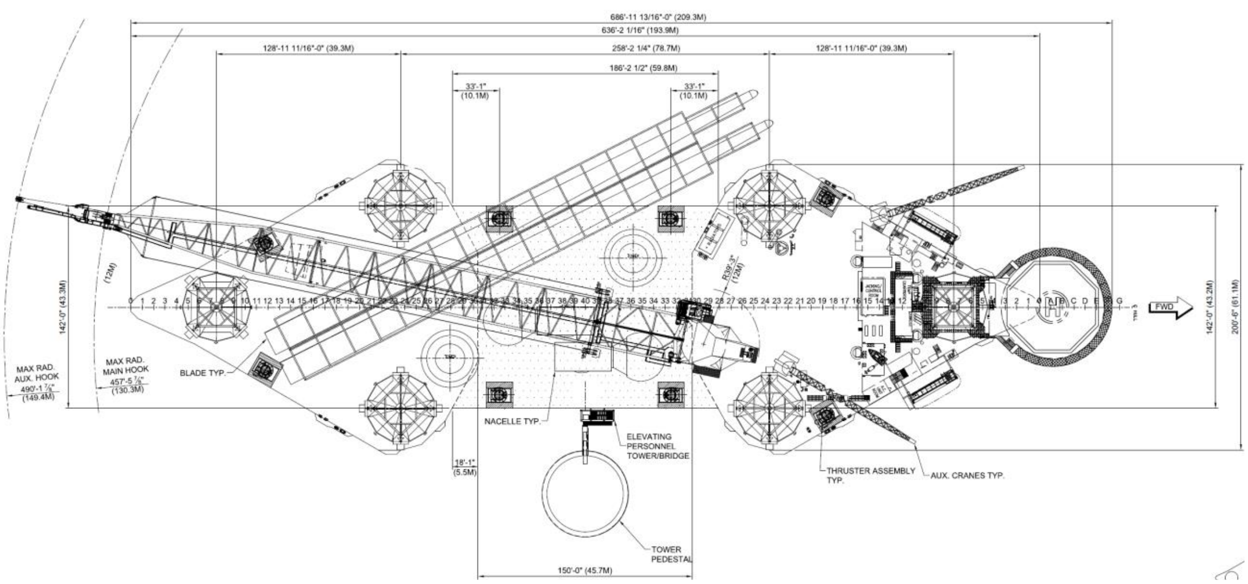
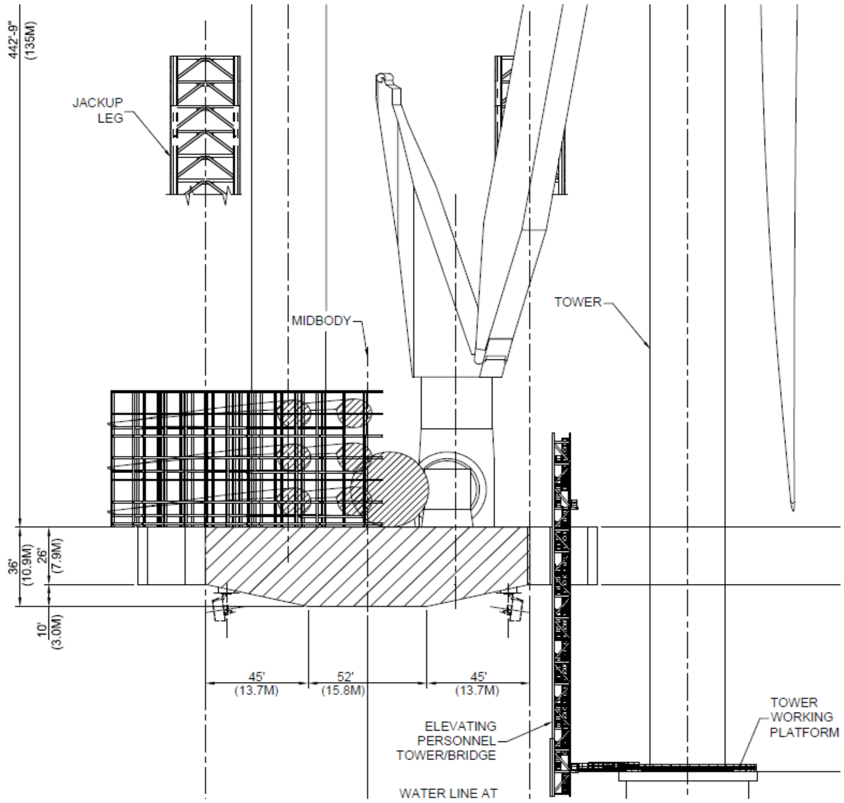


Figure 11. Section View - WTIV Full Depth Midbody.

Section view of the Full Depth Midbody option for the WTIV as developed in Phase 1 of the project.



When developing the draft midbody scantlings calculations, some initial work was done to check the potential weight of the full depth section. With more detailed calculations it was determined that this section offered an acceptable amount of weight to conform to the overall requirements of the WTIV to maintain cargo capacity for two sets of turbine equipment. Therefore this full depth midbody option was utilized for the full midbody scantling calculations and the material take-off (i.e. those Phase 1 items that were still pending at the time of this confirmation).

Details of the material handling study completed in Phase 1 are found in the Document “D02.03 Material Handling Sequence Drawings (DRAFT)”. A preliminary midbody scantlings and material take-off was also completed in Phase 1 with the details found in the Document “D05.01 Memorandum - Midbody Scantlings and Material Take-Off (DRAFT)” and illustrations of the midbody scantlings shown in Document “D05.02 Drawing - Midbody Scantlings (DRAFT)”.

3.3 Preliminary Lightship Estimate and Variable Load Condition Development

As noted in Section 3.2, the wing deck layout option was utilized for the draft version of the preliminary lightship estimate and variable load condition development. A hull model was developed using General Hydrostatics (GHS) stability software based on the LeTourneau Model 116C jack-up hulls and modified to include the wing deck midbody section. Hydrostatics were run for zero trim, 0.5m forward and 0.5m aft trim up to the WTIV hull depth of 26ft for use as part of subsequent load condition calculations.

The lightship data was developed considering steel and equipment removals from the LeTourneau Model 116C jack-ups, as well as steel additions for the new midbody and equipment additions for the turbine installation functionality of the vessel. The jack-up cantilever assembly has already been removed and is not included in the jack-up lightship value listed below (for both the forward and aft jack-ups).

Items being removed from the jack-ups include the following:

- Cantilever assemblies (already separated from jack-up lightship and not included below)
- Mud pumps
- Charging/Mixing and piping
- Mud pits
- Mud process equipment/tanks
- Dry bulk tanks and piping
- Service cranes and pedestals
- Quarters and helideck (aft jack-up only)

Items being added to the WTIV include the following:

- Midbody section
- Main cargo crane
- Thrusters

The lightship data is presented in Table 2. The vertical reference is the bottom of the midbody section which is 10ft below the baseline of the jack-up hulls. The longitudinal reference is the center of the midbody section.

Table 2. WTIV Lightship Estimate for Phase 1.

Lightship component estimates including the jack-up components and midbody section, as well as turbine installation components as developed in Phase 1 of the project.

	Component Description	Weight		LCG	TCG	VCG
		(kips)	(MT)	(ft from 0, + aft)	(ft fr CL, +stbd)	(ft abv midbody BL)
FORWARD JACK-UP						
	Forward Jack-up Lightship	9,518	4,317	-275.08	0.15	44.56
	Forward Jack-up Legs	7,741	3,511	-172.04	0.00	211.41
Remove	Mud Pumps (x3)	-165	-75	-137.91	0.00	19.50
	Charging/Mixing and Piping	-110	-50	-137.91	0.00	19.50
	Mud Pits	-55	-25	-137.91	0.00	19.50
	Mud Process Equipment/Tanks	-150	-68	-137.91	0.00	19.50
	Dry Bulk Tanks & Piping	-50	-23	-137.91	0.00	23.00
Add	Thruster 6 (Forward Port)	209	95	-168.85	-75.84	23.00
	Thruster 7 (Forward Stbd)	209	95	-168.85	75.84	23.00
AFT JACKUP						
	Aft Jack-up Lightship	9,518	4,317	275.08	-0.15	44.56
	Aft Jack-up Legs	7,741	3,511	172.04	0.00	211.41
Remove	Mud Pumps (x3)	-165	-75	137.91	0.00	19.50
	Charging/Mixing, and Piping	-110	-50	137.91	0.00	19.50
	Mud Pits	-55	-25	137.91	0.00	19.50
	Mud Process Equipment/Tanks	-150	-68	137.91	0.00	19.50
	Dry Bulk Tanks & Piping	-50	-23	137.91	0.00	23.00
	Service Cranes & Pedestals (Port)	-50	-23	148.66	42.94	68.50
	Service Cranes & Pedestals (Stbd)	-50	-23	210.65	64.59	519.97
	Quarters	-1,080	-490	212.87	0.00	47.63
	Helideck	-21	-10	318.08	0.00	50.40
Add	Thruster 1 (Aft Port)	209	95	224.02	-44.04	23.00
	Thruster 2 (Aft Stbd)	209	95	224.02	44.04	23.00
MIDBODY & EQUIPMENT						
	Main Crane (1200 MT capacity)	2,967	1,346	10.14	6.71	125.09
	New Midbody (steel)	3,469	1,574	0.00	0.00	19.80
	Thruster 3 (Midbody Aft Stbd)	209	95	60.02	61.66	23.00
	Thruster 4 (Midbody Forward Stbd)	209	95	-60.02	61.66	23.00
	Thruster 5 (Midbody Forward Port)	209	95	-60.02	-61.66	23.00
	NEW LIGHTSHIP	40,155	18,214	-5.33	0.68	111.86

A total of three variable load conditions were developed in Phase 1, as follows:

- Transit condition with legs jacked up and turbine equipment on board ("Transit").
- Leg Installation condition with legs near bottom and turbine equipment on board ("Legs Deployed").
- Operating condition with turbine equipment installation operations underway ("Elevated").

A WTIV load condition spreadsheet was created listing all consumable tanks, major weight items for the new lightship and cargo packages for two 15MW turbines arranged on the deck.

For the Transit Condition with all consumable tanks filled to 95%, two 15MW turbine packages on deck, and the legs fully raised, the WTIV was floating at a draft of 22.10ft at 0.0 degrees trim and 0.0 degrees heel. The GM is 21.63ft including free surface corrections. Note that this is a draft of 12.10ft on the original jack-up hulls.

For the Legs Deployed Condition with all consumable tanks filled to 95%, two 15MW turbine packages on deck, and the legs lowered to 338ft (103m), the WTIV was floating at a draft of 22.10ft at 0.0 degrees trim and 0.0 degrees heel. The GM is 120.08ft including free surface corrections. No consideration was given to the buoyant volume of the legs.

The Elevated Condition incorporated the water depth, leg penetration, and air gap to define the vertical position of the WTIV and hence the crane hook height. The crane hook load was transferred from its storage position on the deck to the hook to allow for checking the leg loads against the holding limits. The Elevated Condition considered the longitudinal position of each leg relative to the total LCG without the legs, to determine the total jacking load on each leg. This distribution assumed the hull is sufficiently stiff to fully distribute the loads to the various legs. This is not necessarily the case but at this level of analysis the assumption provided a useful review of the condition. Utilizing a reasonable margin on the maximum jacking capacity and holding load limit during crane lift operations enabled a satisfactory confidence level that these limits will not be exceeded.

Details of these tasks completed in Phase 1 are found in the Document "D03.01 Memorandum - Preliminary Loading Conditions and Stability Check (DRAFT)".

3.4 Preliminary Motions Assessment

A hull surface model was developed using Rhinoceros 3D software (Rhino) based on the LeTourneau Model 116C jack-up hulls and modified to include the wing deck midbody section. A hydrodynamic diffracting mesh model was then created using the ANSYS AQWA 3D Hydrodynamics software suite (AQWA). This model was created using the final WTIV Rhino model.

An isometric view of the Rhino WTIV model is shown in Figure 12 where the leg wells can be seen in addition to the new midship section with its wing deck profile. Plan and elevation views are shown in Figure 13 and Figure 14. Note that this model includes the wing decks while the AQWA hydrodynamic diffracting model is only defined up to the waterline which sits below the level of the wing decks.

Figure 12. Isometric View – WTIV Rhino Model.

Isometric view for the WTIV Rhino Model illustrating the leg wells (red shapes) and midbody section details as developed in Phase 1 of the project.

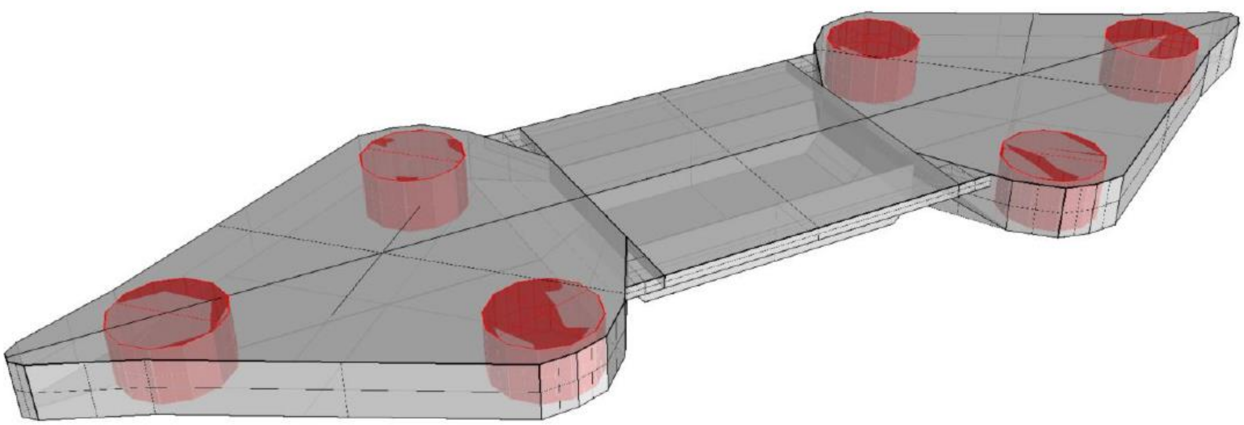


Figure 13. Plan View – WTIV Rhino Model.

Plan view for the WTIV Rhino Model illustrating the leg wells and midbody section addition as developed in Phase 1 of the project.

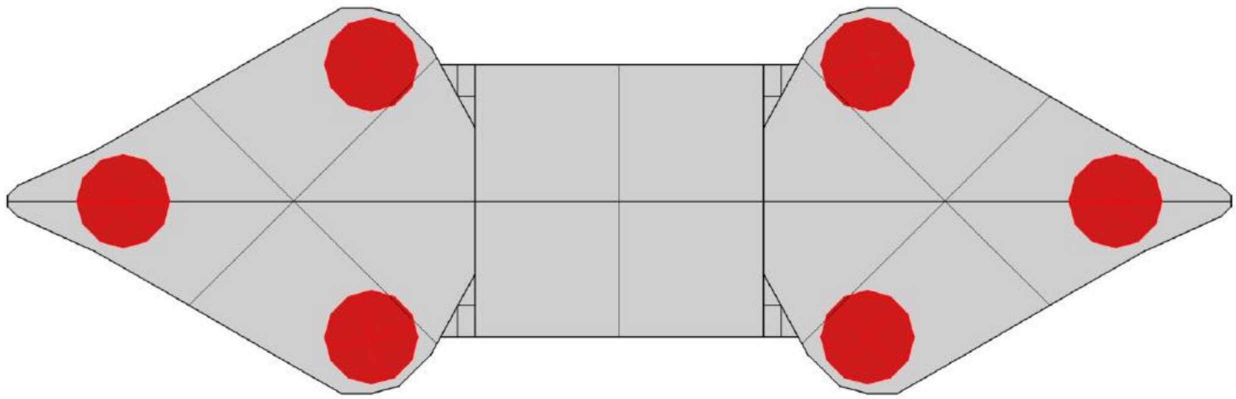
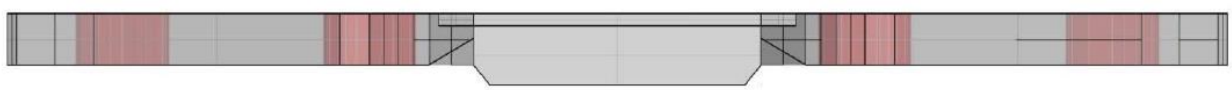


Figure 14. Elevation View – WTIV Rhino Model.

Elevation view for the WTIV Rhino Model illustrating the leg wells and the deep middle section of the midbody with the wing deck side sections as developed in Phase 1 of the project.



The two floating load conditions developed earlier in Phase 1 were considered in the motions assessment. Response Amplitude Operators (RAOs) were developed for each load condition through motions analyses performed using AQWA. Results for the Transit Condition in significant wave heights of 5.74 ft with a 9.43 second dominant period are presented in Table 3.

Table 3. Motions Results – Transit Condition

Motions results for the Transit Condition with draft of 22.18 ft and headings of 180-, 135-, and 90-degrees as developed in Phase 1 of the project.

Heading (deg)	Max Vessel Excursions at COG			Max Vessel Accelerations at COG		
	Heave (ft)	Roll (deg)	Pitch (deg)	Heave (ft/s^2)	Roll (deg/s^2)	Pitch (deg/s^2)
180	2.351	0.004	1.540	0.530	0.000	0.427
135	3.292	4.126	1.499	0.776	0.193	0.496
90	5.144	3.773	0.012	1.850	0.244	0.005

Results for the Legs Deployed Condition in significant wave heights of 5.74 ft with a 9.43 second dominant period are presented in Table 4**Error! Reference source not found.**.

Table 4. Motions Results – Legs Deployed Condition

Motions results for the Legs Deployed Condition with draft of 22.18 ft and headings of 180-, 135-, and 90-degrees as developed in Phase 1 of the project.

Heading (deg)	Max Vessel Excursions at COG			Max Vessel Accelerations at COG		
	Heave (ft)	Roll (deg)	Pitch (deg)	Heave (ft/s^2)	Roll (deg/s^2)	Pitch (deg/s^2)
180	2.177	1.083	1.700	0.527	0.000	0.431
135	2.983	2.780	1.665	0.773	0.317	0.486
90	4.979	4.136	0.121	1.839	0.618	0.003

Details of this assessment completed in Phase 1 are found in the Document "D04.01 Memorandum - Preliminary Motions Assessment (DRAFT)".

4 Phase 2 Developments

Phase 2 tasks, termed “Naval Architecture Finalization”, focused on completion of those tasks started in Phase 1 through a second design cycle to adjust and finalize concept details. Due to issues found in the calculations of the midbody scantlings work completed in Phase 1, several of these tasks were delayed while the midbody work was corrected. Details of the individual tasks are expanded upon in the following subsections.

4.1 Preliminary Longitudinal Strength Assessment

The preliminary longitudinal strength assessment was the starting point of the work in this phase. Partway through this assessment it was determined that certain computational errors had occurred in the application of the minimum structural scantling calculations during the Phase 1 midbody scantling work. Specifically, the contribution of certain transverse structural members was erroneously incorporated to contribute to the longitudinal strength of the midbody.

Considering this issue, it was required that an updated wing deck style midbody be developed. Three options were reviewed with one selected for use in the other work items for Phase 2 and beyond. For all three options the same footprint and cargo area were retained to essentially “delete” any need to re-assess the deck layout. The calculations for the options are presented in “D06.01 Report – Longitudinal Strength Assessment (DRAFT)”, which was conducted in conjunction with the midbody option development to ensure adequate minimum scantlings were achieved for the midbody structure.

Cursory results from the assessment indicated that the new midbody would fare well with sufficient strength margin during all lifting conditions, however the forward jack-up failed to provide minimal margins of strength near the crane location and the legs near the crane were overloaded due to the proximity of the crane. This demonstrated that the jack-up hull’s strength will be critical to this design. It should be noted that the transition structure between the midbody section and jack-up hulls was not included as part of the assessment. It is anticipated that as part of more detailed design the transition structure will serve to better distribute loads and transition the stiffness between hulls, thereby reducing stress concentrations and fatigue issues. Review of the results also showed that the load sharing between the legs is not equal - the center four legs support the majority of the WTIV.

Moving forward to Phase 3, certain issues needed to be addressed to improve the results of the longitudinal strength assessment to an acceptable level. These included the following:

- Update the WTIV layout with relocation of the crane to better distribute crane induced bending loads and reduce imbalanced loading of jacking legs.
  - This will require shifting the crane to the centerline and nearer the center of the midbody.
  - Location will be decided based on maximizing overall unit capacity and minimizing the need for additional structural reinforcements.

- The new crane location will require the removal of the aft most jack-up leg and trimming of the aft section to reduce overall unit weight to maintain unit lift capacity.
  - Minimal load being transmitted to the aftmost jacking leg.
  - Removal allows for storage of the crane boom directly aft (no interference between boom and legs).
  - Removal of aft leg also improves wind drag area for stability considerations.

Details of this assessment completed in Phase 2 are found in the Document "D06.01 Report – Longitudinal Strength Assessment (DRAFT)".

4.2 General Arrangements, Midbody Scantlings, and Material Handling

As noted in the previous subsection, an updated midbody section was developed that did not have an impact on the deck layout. The following figures provide views of the WTIV that includes the latest midbody section. Figure 15 shows the plan view.

Figure 16 depicts the section shape of the latest midbody section.

Figure 15. Plan View – WTIV General Arrangement.

Plan view of the WTIV illustrating the deck layout and general concept as developed in Phase 2 of the project.

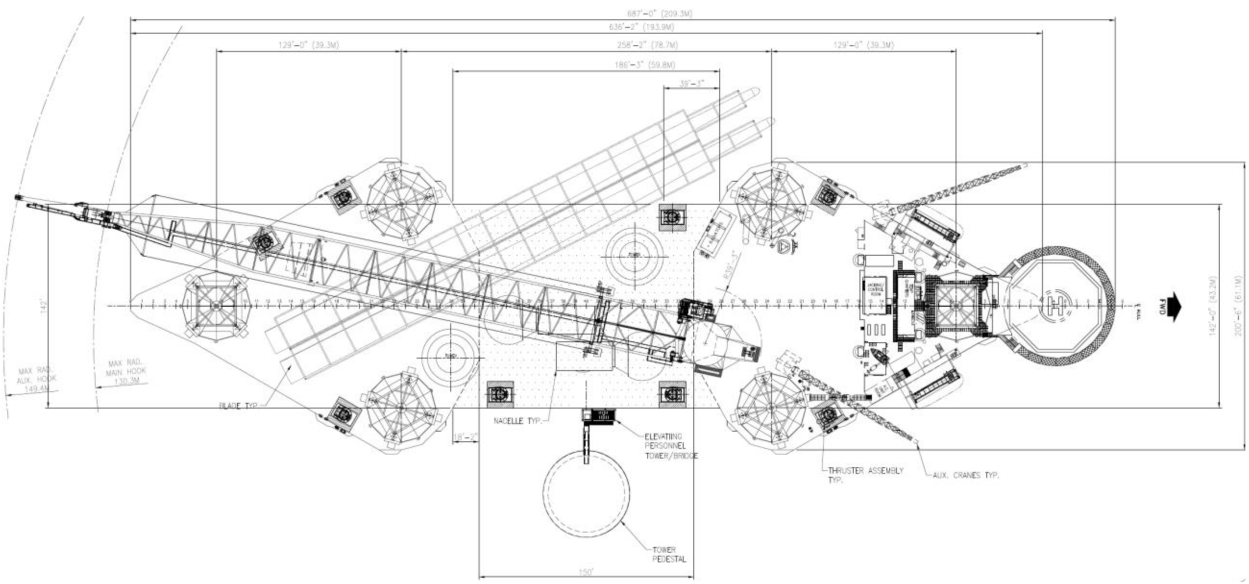
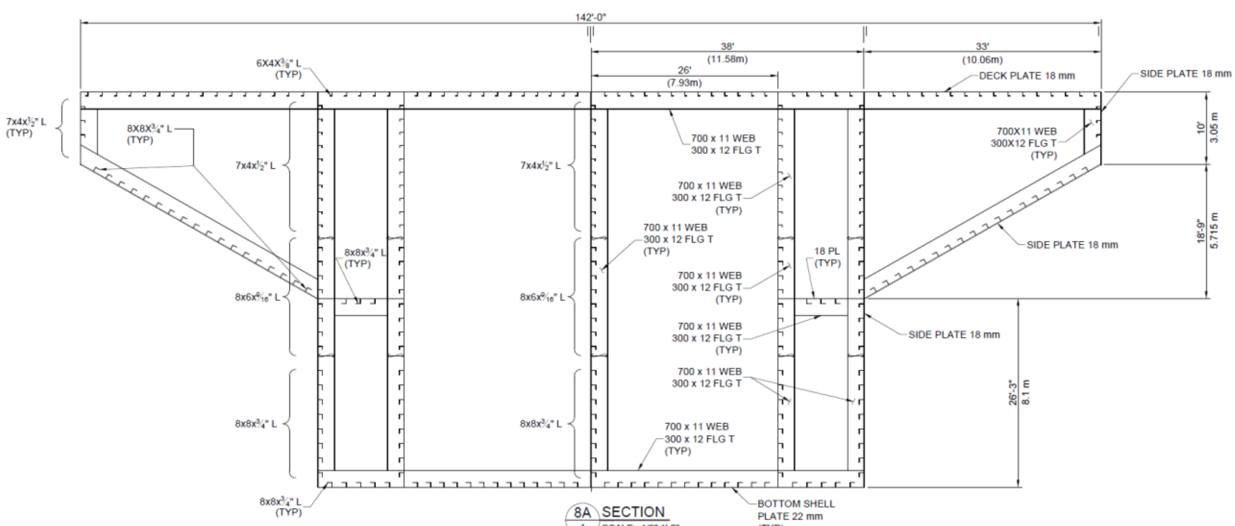


Figure 16. Section View - WTIV Full Depth Midbody.

Section view of the latest midbody section for the WTIV illustrating the typical framing and bulkhead details as well as the general section shape as developed in Phase 2 of the project.



The material handling study was finalized in Phase 2 with details found in the Document “D02.06 Material Handling Sequence Drawings”. The updated midbody scantlings and material take-off was also completed with the details found in the Document “D05.03 Memorandum - Midbody Scantlings and Material Take-Off” and illustrations of the midbody scantlings shown in Document “D05.04 Drawing - Midbody Scantlings”.

4.3 Lightship Estimate, Variable Load Condition Development, and Stability Check

The work done for these tasks in Phase 1 were taken as a baseline for their Phase 2 completion. The GHS hull model was updated to account for the updated midbody and hydrostatics were re-run. Consideration for tanks in the midbody were also incorporated (fresh water and fuel tanks) to allow for greater adjustments in the load conditions. The lightship estimate was updated based on the concept updates made throughout Phase 2 and is presented in Table 5. The vertical reference is the bottom of the midbody section which is 10ft below the baseline of the jack-up hulls. The longitudinal reference is the center of the midbody section.

Table 5. WTIV Lightship Estimate for Phase 2.

Lightship component estimates including the jack-up components and midbody section, as well as turbine installation components as developed in Phase 2 of the project.

	Component Description	Weight		LCG	TCG	VCG
		(kips)	(MT)	(ft from 0, + aft)	(ft fr CL, +stbd)	(ft abv midbody BL)
FORWARD JACK-UP						
	Forward Jack-up Lightship	9,518	4,317	-275.08	0.15	63.56
	Forward Jack-up Legs	7,741	3,511	-172.04	0.00	218.24
Remove	Mud Pumps (x3)	-165	-75	-137.91	0.00	38.50
	Charging/Mixing and Piping	-110	-50	-137.91	0.00	38.50
	Mud Pits	-55	-25	-137.91	0.00	38.50
	Mud Process Equipment/Tanks	-150	-68	-137.91	0.00	38.50
	Dry Bulk Tanks & Piping	-50	-23	-137.91	0.00	42.00
Add	Thruster 6 (Forward Port)	209	95	-168.85	-75.84	42.00
	Thruster 7 (Forward Stbd)	209	95	-168.85	75.84	42.00
AFT JACKUP						
	Aft Jack-up Lightship	9,518	4,317	275.08	-0.15	63.56

	Aft Jack-up Legs	7,741	3,511	172.04	0.00	218.24
Remove	Mud Pumps (x3)	-165	-75	137.91	0.00	38.50
	Charging/Mixing, and Piping	-110	-50	137.91	0.00	38.50
	Mud Pits	-55	-25	137.91	0.00	38.50
	Mud Process Equipment/Tanks	-150	-68	137.91	0.00	38.50
	Dry Bulk Tanks & Piping	-50	-23	137.91	0.00	42.00
	Service Cranes & Pedestals (Port)	-50	-23	148.66	-42.94	68.50
	Service Cranes & Pedestals (Stbd)	-50	-23	210.65	64.59	68.50
	Quarters	-1,080	-490	212.87	0.00	66.63
	Helideck	-21	-10	318.08	0.00	69.40
Add	Thruster 1 (Aft Port)	209	95	224.02	-44.04	42.00
	Thruster 2 (Aft Stbd)	209	95	224.02	44.04	42.00
MIDBODY & EQUIPMENT						
	Main Crane (1200 MT capacity)	2,920	1,325	10.14	6.71	144.09
	New Midbody (steel)	4,988	2,263	0.00	0.00	29.69
	Thruster 3 (Midbody Aft Stbd)	201	91	0.00	0.00	42.00
	Thruster 4 (Midbody Forward Stbd)	209	95	60.02	61.66	42.00
	Thruster 5 (Midbody Forward Port)	209	95	-60.02	61.66	42.00
	Thruster 8 (Midbody Aft Port)	209	95	-60.02	-61.66	42.00
	FWD Jacking Motors & Pinions	150	68	-172.04	0.00	41.00
	AFT Jacking Motors & Pinions	150	68	172.04	0.00	41.00
	NEW LIGHTSHIP	42,338	19,205	-4.77	0.44	120.97

A total of four variable load conditions were considered in Phase 2 as follows:

- Transit condition with legs jacked up and turbine equipment on board (“Transit”).
- Leg Installation condition with legs near bottom and turbine equipment on board (“Legs Deployed”).
- Operating condition with turbine equipment installation operations underway (“Elevated”).
- Transit condition with legs jacked up and no turbine equipment on board (“No Cargo”).

The “No Cargo” condition was not included in the Phase 1 checks. The WTIV load condition spreadsheet was updated to include this condition as well as to update for changes made in Phase 2.

For the No Cargo Condition with no turbine components on deck, and the legs fully raised, the WTIV was floating at a draft of 34.94 ft at 0.0 degrees trim and 0.0 degrees heel. The GM is 45.47ft including free surface corrections. Note that this is a draft of 5.94ft on the original jack-up hulls.

For the Transit Condition with two 15MW turbine packages on deck, and the legs fully raised, the WTIV was floating at a draft of 36.48 ft at 0.0 degrees trim and 10.0 degrees heel (starboard). The GM is 30.37ft including free surface corrections. Note that this is a draft of 7.48ft on the original jack-up hulls.

For the Legs Deployed Condition with two 15MW turbine packages on deck, and the legs lowered to 349ft, the WTIV was floating at a draft of 36.48 ft at 0.0 degrees trim and 0.26 degrees heel (starboard). The GM is 118.73ft including free surface corrections. No consideration was given to the buoyant volume of the legs.

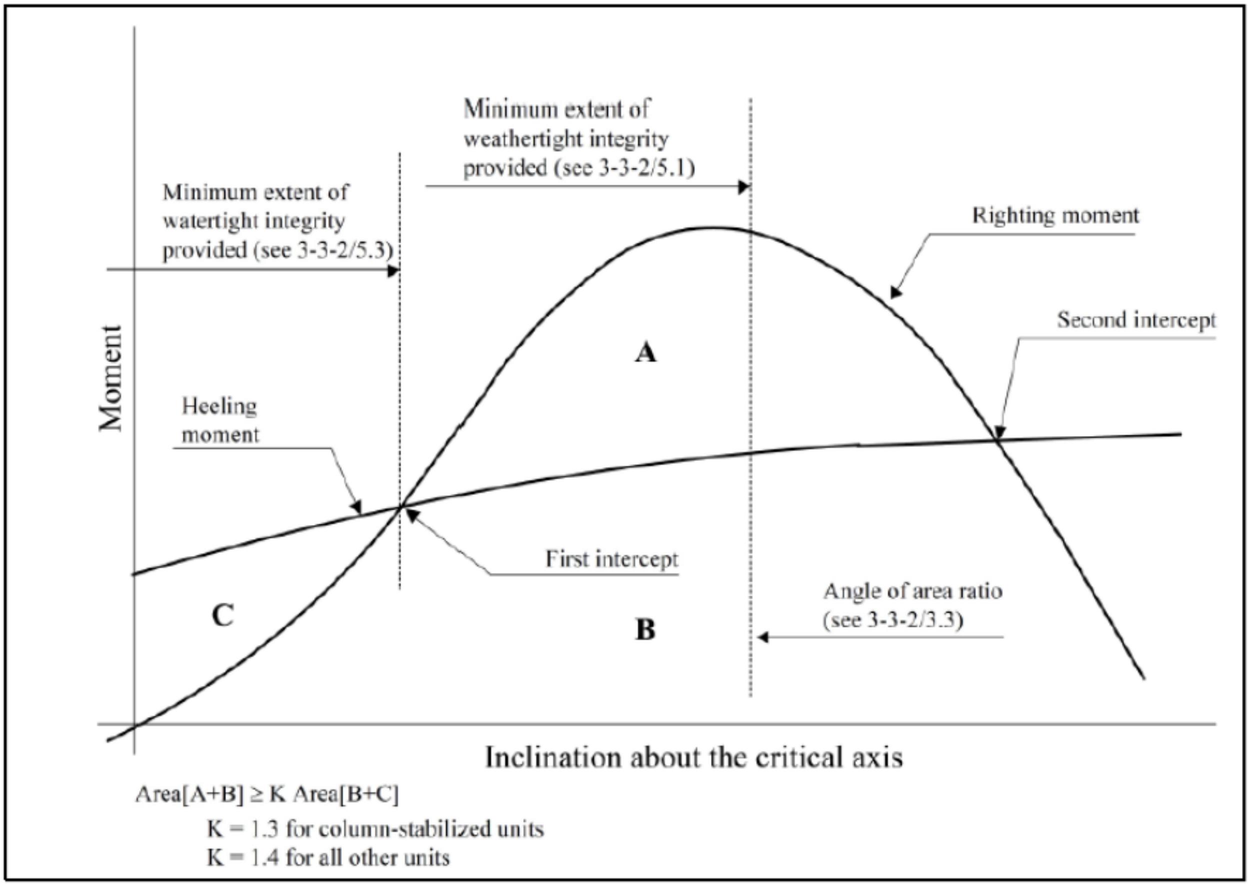
The Elevated Condition incorporated the water depth, leg penetration, and air gap to define the vertical position of the WTIV and hence the crane hook height. The crane hook load was transferred from its storage position on the deck to the hook to allow for checking the leg loads against the holding limits. The Elevated Condition considered the longitudinal position of each leg relative to the total LCG without the legs, to determine the total jacking load on each leg. This distribution assumed the hull is sufficiently stiff to fully distribute the loads to the various legs. This is not necessarily the case but at this level of analysis the assumption provided a useful review of the condition. Utilizing a reasonable margin on the maximum jacking capacity and holding load limit during crane lift operations enabled a satisfactory confidence level that these limits will not be exceeded.

Intact stability was also checked as part of the Phase 2 work. This was checked for all three of the floating load conditions against the Intact Stability limits set by ABS Rules for Mobile Offshore Units:

- Limit 1 – Positive GM Transit condition.
    - Chapter 3-3-2/1.1 states all units are to have positive metacentric height in calm water equilibrium positions for all afloat conditions, including temporary positions when raising or lowering.
- Limit 2 – Absolute Ratio from 0 to RA0 or Flood > 1.4.
    - Chapter 3-3-2/3.3.1 states for self-elevating units and surface type units, the righting energy (area under the righting moment curve) at or before the angle of the second intercept of the righting and the heeling moment curves of the downflooding angle, whichever is less, is to reach a value of not less than 40% in excess of the area under the heeling moment curve to ethe same limiting angle as indicated in 3-3-2/3.3. Please refer to XXX for a graphical representation of Limit 2.

Figure 17. Intact Stability Curve from ABS Rules for Mobile Offshore Units.

Graphical representation of the intact stability curve from ABS Rules for Mobile Offshore Units for Limit 2.



ABS Rules state: "Units not designed to withstand the above heeling moments will be considered for classification for "Restricted Service" in association with a heeling moment equivalent to a minimum wind speed of 25.8 m/s (50 knots). (3-3-2/1.3.1)".

Based on these load conditions, the intact stability was calculated with results presented in Table 8.

Table 6. Motions Results – Intact Stability Results.

Results of the intact stability check for the identified WTIV load conditions.

Conditions	Range	Wind Speed	HMMT	MOU Criteria	
				Limit 1	Limit 2
	(deg)	(knots)	(kip-ft)	(ft)	
No Cargo	14.13	52.70	104,128	45.3	1.4
Transit	12.76	35.80	76,785	30.4	1.4
Legs Deployed	19.67	100.00	320,713	118.7	4.0

The No Cargo (transit) condition of the WTIV complies with Limit 2 up to a 52.7 knot wind. In the case of the WTIV Transit condition (with cargo onboard), the vessel does not comply with Limit 2 in 50 knot winds. The wind speed was reduced until Limit 2 was acceptable. For the Transit, the vessel will pass with a wind speed of 35.8 knots. In the Legs Deployed condition, the WTIV will pass with wind speeds greater than 50 knots. It can be seen from the results that wind drag on the jacking legs and turbine towers is a key driver of the WTIV stability. This is due to the large wind area presented high above the WTIV hull.

Details of these tasks completed in Phase 2 are found in the Document "D03.03 Memorandum - Preliminary Loading Conditions and Stability Check".

4.4 Motions Assessment

The work done for this assessment in Phase 1 were taken as a baseline for its Phase 2 completion. The Rhino hull surface model was updated based on changes in Phase 2 which was used to update the AQWA hydrodynamic diffracting mesh model.

An isometric view of the Rhino WTIV model is shown in Figure 18 where the leg wells can be seen in addition to the latest midship section with its wing deck profile. An isometric view of the AQWA diffraction model is shown in Figure 19.

Figure 18. Isometric View – WTIV Rhino Model (Phase 2).

Isometric view for the WTIV Rhino hull model illustrating the leg wells (blue shapes) and midbody section details as developed in Phase 2 of the project.

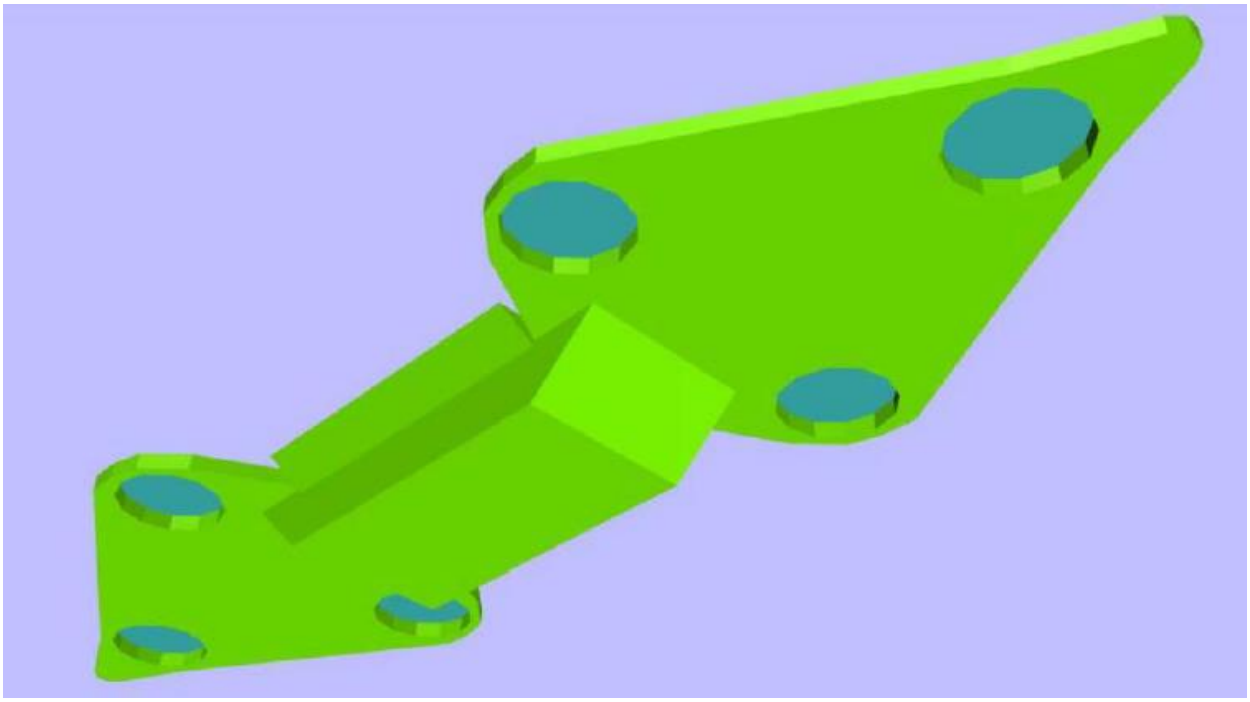
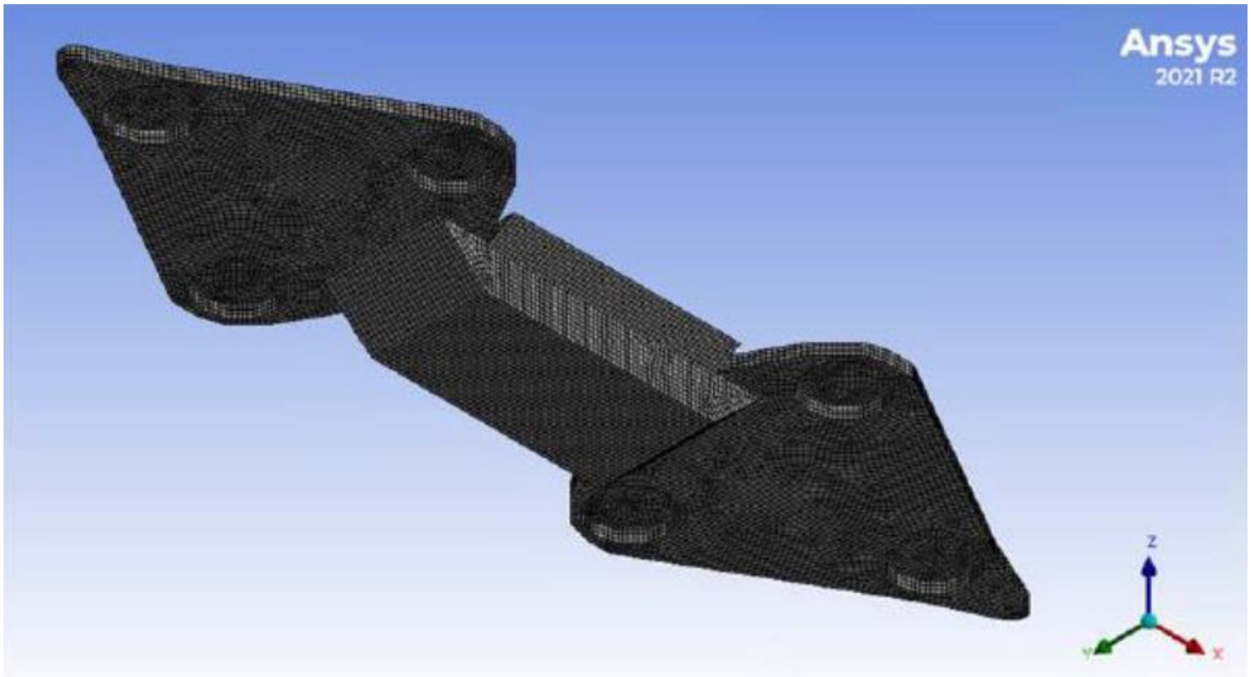


Figure 19. Isometric View – WTIV AQWA Model (Phase 2).

Isometric view for the WTIV AQWA diffraction model illustrating the leg wells and midbody section details as developed in Phase 2 of the project.



The two floating load conditions considered in Phase 1 were considered in the motions assessment, along with an additional Survival (Transit) case. Response Amplitude Operators (RAOs) were developed for each load condition through motions analyses performed using AQWA.

Results for the Transit Condition in significant wave heights of 5.74 ft with a 9.43 second dominant period are presented in Table 7.

Table 7. Motions Results – Transit Condition (Phase 2)

Motions results for the Transit Condition with draft of 36.48 ft and headings of 180-, 135-, and 90-degrees as developed in Phase 2 of the project.

Heading (deg)	Max Vessel Excursions at COG			Max Vessel Accelerations at COG		
	Heave (ft)	Roll (deg)	Pitch (deg)	Heave (ft/s^2)	Roll (deg/s^2)	Pitch (deg/s^2)
180	2.154	0.000	1.516	0.455	0.000	0.415
135	2.926	0.775	1.489	0.721	0.120	0.482
90	4.735	0.280	0.000	1.670	0.070	0.000

Results for the Legs Deployed Condition in significant wave heights of 5.74 ft with a 9.43 second dominant period are presented in Table 8**Error! Reference source not found.**.

Table 8. Motions Results – Legs Deployed Condition (Phase 2)

Motions results for the Legs Deployed Condition with draft of 36.48 ft and headings of 180-, 135-, and 90-degrees as developed in Phase 2 of the project.

Heading (deg)	Max Vessel Excursions at COG			Max Vessel Accelerations at COG		
	Heave (ft)	Roll (deg)	Pitch (deg)	Heave (ft/s^2)	Roll (deg/s^2)	Pitch (deg/s^2)
180	2.102	0.000	1.609	0.459	0.000	0.428
135	2.915	2.310	1.563	0.713	0.391	0.466
90	4.779	3.863	0.000	1.655	0.729	0.000

Results for the Survival (Transit) Condition in significant wave heights of 17.06 ft with a 9.65 second dominant period are presented in Table 9**Error! Reference source not found.**

Table 9. Motions Results – Survival Transit (Phase 2)

Motions results for the Survival (Transit) Condition with draft of 36.48 ft and headings of 180-, 135-, and 90-degrees as developed in Phase 2 of the project.

Heading (deg)	Max Vessel Excursions at COG			Max Vessel Accelerations at COG		
	Heave (ft)	Roll (deg)	Pitch (deg)	Heave (ft/s^2)	Roll (deg/s^2)	Pitch (deg/s^2)
180	6.856	0.001	4.559	1.402	0.000	1.218
135	9.230	5.903	4.369	2.130	0.493	1.406
90	15.055	1.722	0.000	5.009	0.218	0.000

Details of this assessment completed in Phase 2 are found in the Document "D04.02 Memorandum - Preliminary Motions Assessment".

5 Phase 3 Developments

Phase 3 tasks, termed "Concept Completion", was based on finalization of the structural assessments and completion of the remaining concept details.

5.1 Longitudinal Strength Assessment

Finalization of the longitudinal strength assessment took place in Phase 3. The first step was to make the layout adjustments as noted at the end of Phase 2 in order to support the re-run of the longitudinal strength assessment. Results of the layout adjustment are reflected in Figure 20 and Figure 21.

In addition to the layout changes, it was determined that as part of the leg removal, the overall jacking capacity of the WTIV was reduced beyond the level required to elevate the WTIV, even after considering the weight reductions associated the leg removal.

The total jacking capacity had been 40,500 kips (18,371 MT), with each pinion holding a capacity of 337.5 kips/pinion (a total of 6,750 kips per leg). There was a total of six legs and each leg had four chords, with five pinions per chord (four original with one added as part of the WTIV modifications). Removing the aft leg reduced the total jacking capacity to 33,750 kips. In order to achieve adequate jacking, it has been considered that an additional row of pinions will be added to the remaining legs. These extra pinions result in an additional 6,650 kips of jacking, which returns the total capacity to 40,500 kips. Additionally, the midbody was revisited to help reduce weight through reduction of the main deck and bottom plate thickness while maintaining adequate Section Modulus.

Figure 20. Plan View – WTIV General Arrangement with Phase 3 Updates.

Plan view for the current WTIV illustrating the deck layout and general concept.

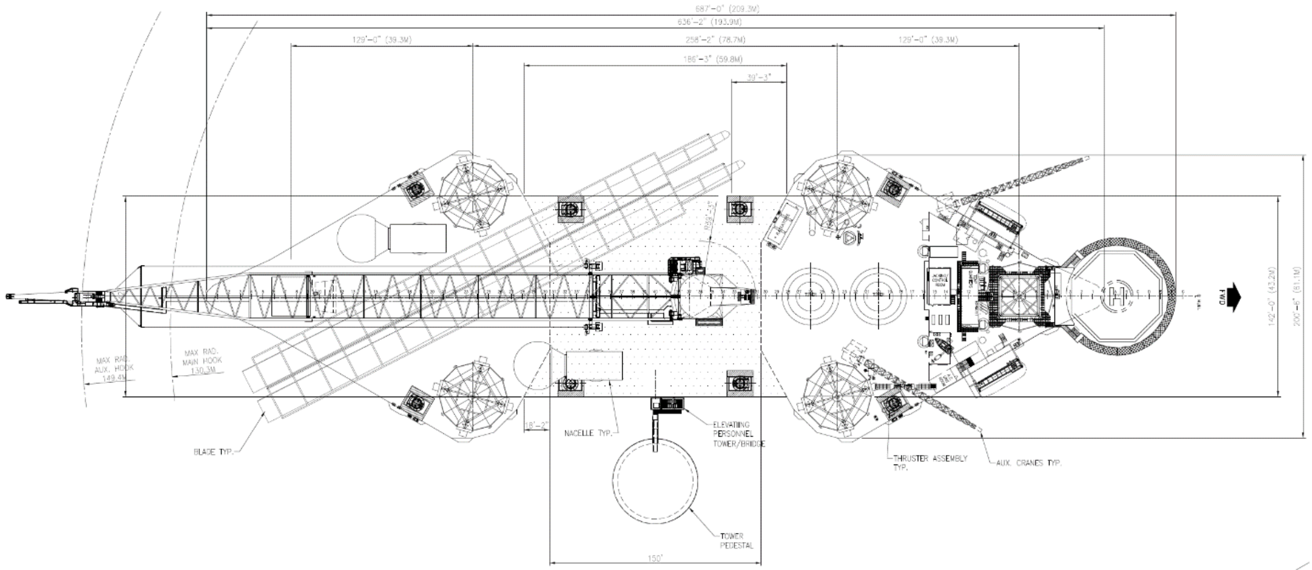
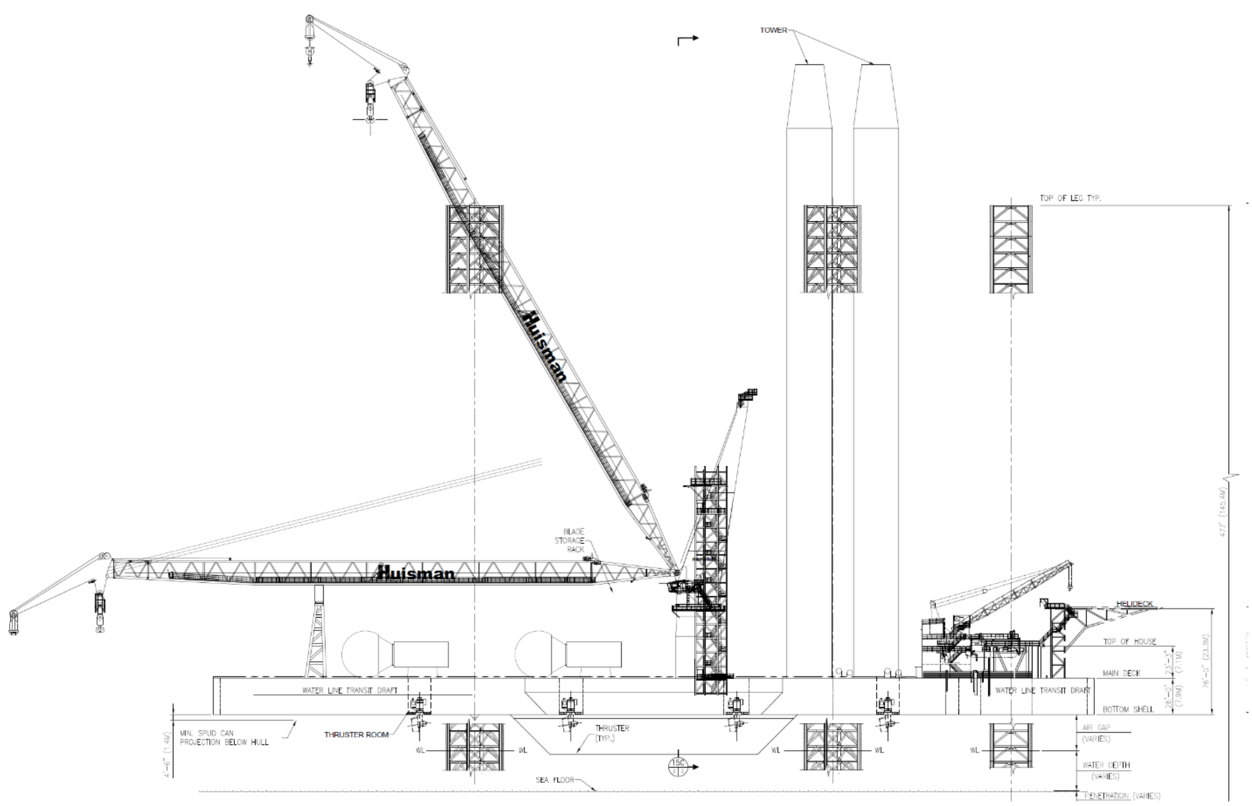


Figure 21. Elevation View – WTIV General Arrangement with Phase 3 Updates.

Elevation view for the current WTIV illustrating the deck layout and general concept.



Cursory results from this updated assessment indicated the midbody and forward jack-up would fare well with sufficient margin when lifting a nacelle under the given tankage and deck cargo as well as under the assumptions that have been made for the crane load chart and jack-up hull structure. The aft jack-up hull failed to provide minimal margins of strength.

As previously noted, the jack-up hull structure is simplified with some assumptions taken from similarly sized jack-ups where some information may not have been available for the LeTourneau 116C. Nonetheless, the section properties provided for the jack-up hulls are sufficiently reasonable for this analysis. Hence, the results demonstrate the aft jack-up hull's strength will be critical to this design.

Also previously noted, the transition structure between midbody and jack-up hulls is not included. It is anticipated that as part of more detailed design the transition structure will serve to better distribute loads and transition the stiffness between hulls, thereby reducing stress concentrations and fatigue issues.

In terms of next steps for the concept, the aft jack-up results could be improved with further removing equipment and supporting structure (i.e., the aft leg well) related to the removed aft leg with the goal of reducing the bending moment load on the aft jack-up. Additionally, reinforcement of the aft jack-up hull is also a possibility, in conjunction with the transition structure, in order to relieve the overutilizations being experienced in the assessment.

Details of this assessment completed in Phase 3 are found in the Document "D06.02 Report – Longitudinal Strength Assessment".

5.2 Drag and Power Requirements

The preliminary assessment of the WTIV's drag and power requirements were completed in Phase 3. The assessment was conducted as a numerical calculation (i.e., not model testing) based on the hull form in order to determine hull resistance and thus transit speed of the vessel for a specific power range based on the envisioned thrusters for the WTIV.

The WITV's drag was estimated using an empirical formula that considered drag separated into several categories based on the different components that contribute to the overall drag (overall resistance):

- Frictional resistance, R_f.
- Residual resistance (Form drag and Wave-making resistance), R_s.
- Wave drift force (mean load).
- Wind drag.
- Current effect.

Total resistance was estimated for four different environmental scenarios as shown in Table 10.

Table 10. WTIV Total Resistance Scenarios.

Summary of four different environmental scenarios considered in the WTIV Total Resistance calculations.

Conditions	H_s (m)	T_p (s)	Wind (m/s)	Current (m/s)
Calm Water	0.0	0.0	0.0	0.0
SC 1	2.0	5.0	10.0	0.5
SC 2	3.0	7.0	15.0	0.5
SC 3	5.0	9.0	20.0	0.5

Considering the resistance components, the estimated total resistance as a function of WTIV velocity is provided as a graph for in Figure 22 and also numerically in Table 11Table 11. For the total resistance estimate, an extra margin of 25% is added to the frictional and the residual resistance.

Figure 22. WTIV Total Resistance Estimations.

Summary of the WTIV Total Resistance estimations across four different environmental scenarios.

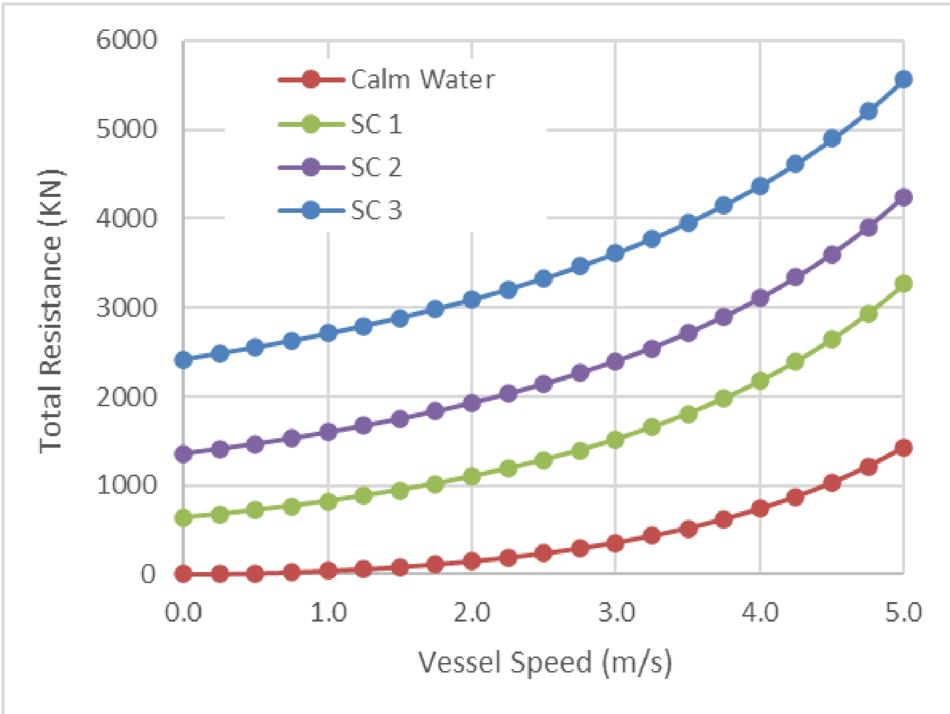


Table 11. WTIV Total Resistance Estimations.

Summary of the WTIV Total Resistance estimations across four different environmental scenarios.

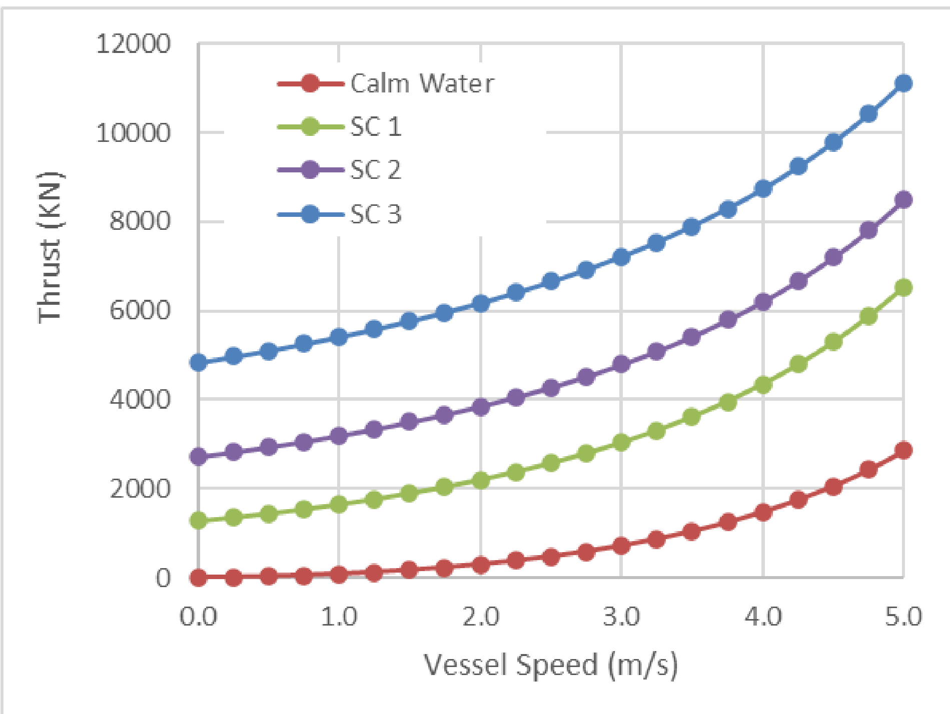
WTIV Velocity (m/s)	R_f (kN)	R_s (kN)	Current Velocity (m/s)	Relative Velocity (m/s)	Relative R_f (kN)	Relative R_s (kN)	Total Resistance Estimate (kN)			
							Calm Water	SC 1	SC 2	SC 3
0.00	0.00	0.00	0.50	0.50	4.31	4.39	0.00	637.23	1359.45	2419.86
0.25	1.21	1.32	0.50	0.75	9.05	9.07	3.16	676.51	1411.67	2485.03
0.50	4.31	4.39	0.50	1.00	15.32	15.46	10.88	720.49	1468.59	2554.89
0.75	9.05	9.07	0.50	1.25	23.04	23.77	22.65	769.33	1530.38	2629.62
1.00	15.32	15.46	0.50	1.50	32.17	34.29	38.47	823.34	1597.34	2709.52
1.25	23.04	23.77	0.50	1.75	42.65	47.41	58.51	882.94	1669.88	2795.01
1.50	32.17	34.29	0.50	2.00	54.46	63.57	83.07	948.65	1748.53	2886.60
1.75	42.65	47.41	0.50	2.25	67.56	83.33	112.58	1021.11	1833.94	2984.96
2.00	54.46	63.57	0.50	2.50	81.92	107.35	147.54	1101.13	1926.90	3090.87
2.25	67.56	83.33	0.50	2.75	97.53	136.41	188.62	1189.64	2028.36	3205.27
2.50	81.92	107.35	0.50	3.00	114.37	171.42	236.60	1287.79	2139.45	3329.31
2.75	97.53	136.41	0.50	3.25	132.41	213.50	292.43	1396.92	2261.52	3464.32
3.00	114.37	171.42	0.50	3.50	151.64	263.93	357.24	1518.62	2396.17	3611.91
3.25	132.41	213.50	0.50	3.75	172.05	324.25	432.38	1654.80	2545.30	3773.99

3.50	151.64	263.93	0.50	4.00	193.62	396.27	519.46	1807.71	2711.15	3952.78
3.75	172.05	324.25	0.50	4.25	216.34	482.13	620.37	1980.00	2896.39	4150.97
4.00	193.62	396.27	0.50	4.50	240.19	584.35	737.36	2174.82	3104.15	4371.67
4.25	216.34	482.13	0.50	4.75	265.17	705.93	873.08	2395.87	3338.15	4618.61
4.50	240.19	584.35	0.50	5.00	291.27	850.36	1030.68	2647.55	3602.77	4896.18
4.75	265.17	705.93	0.50	5.25	318.47	1021.81	1213.87	2935.02	3903.19	5209.54
5.00	291.27	850.36	0.50	5.50	346.77	1225.18	1427.04	3264.41	4245.51	5564.81

The propulsion power requirement estimate was based on the total resistance calculated for the four conditions considered in the study. It is known that propeller efficiency can be significantly reduced due to environments, hull form, and vessel speed. A propeller efficiency of 50% is assumed for the current estimate. Figure 23 provides a graph of the estimated thrust required for the WTIV vessel at various speeds.

Figure 23. WTIV Thrust Estimations.

Summary of the WTIV Thrust estimations across four different environmental scenarios.



Based on the estimated thrust requirement and the thrusters envisioned to be installed on the WTIV (8 x 3,000 HP), one can estimate the maximum vessel speed to be achieved, as shown in Figure 24 and Table

12. As shown, the maximum speed in calm water that can be achieved is estimated to be 12 knots, which reduces to 5 knots with a significant wave height of 5 m and head wind speed of 20 m/s.

Figure 24. WTIV Maximum Speed Estimations.

Summary of the WTIV Maximum Speed estimations across four different environmental scenarios.

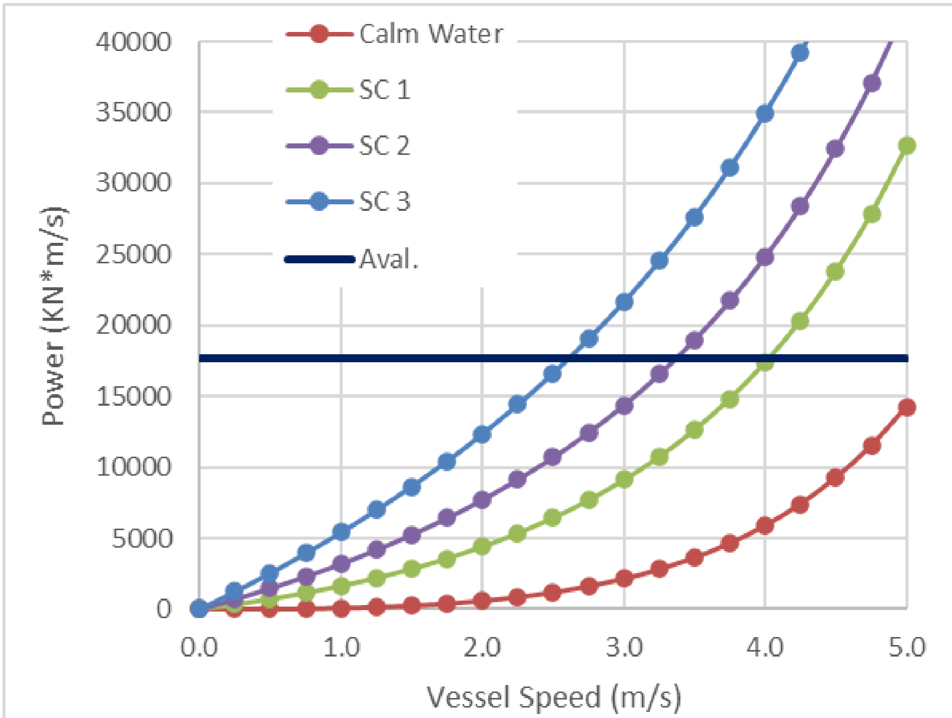


Table 12. WTIV Maximum Speed Estimations.

Summary of the WTIV Maximum Speed estimations across four different environmental scenarios.

Conditions	H_s (m)	T_p (s)	Wind (m/s)	Current (m/s)	Max Speed (m/s)	Max Speed (knots)
Calm Water	0.0	0.0	0.0	0.0	6.2	12.0
SC 1	2.0	5.0	10.0	0.5	4.1	7.9
SC 2	3.0	7.0	15.0	0.5	3.5	6.7
SC 3	5.0	9.0	20.0	0.5	2.7	5.2

From these calculations it was determined that the WTIV could obtain a maximum speed of roughly 12 knots in calm water conditions when utilizing the anticipated set of eight thrusters rated at 3,000 HP per thruster. This maximum speed decreases as the environmental conditions increase, as outlined in the final column of Table 12, with a maximum speed of 5.2 knots considering the most severe environmental scenario included in the study.

Details of this assessment completed in Phase 3 are found in the Document “D07.01 Memorandum – Preliminary Hull Drag and Power Assessment”.

5.3 Jacking System Assessment and Cost Estimate

A jacking system assessment was undertaken to ascertain the status of the modified jacking system to suit the needs of the WTIV. The assessment included the following:

- Determine the jacking speed existing and upgraded jacking system.
- Review the existing jacking leg guidance system and define upgraded system.
- Determine WTIV jacking equipment fatigue life
  - Estimate fatigue under WTIV loading conditions
  - Recommend improvements to the systems to increase fatigue life
- Define jacking system control system for the WTIV and outline jacking procedure and optimization
- Develop preliminary equipment list and weight estimate.

Please refer to the Document “D08.01 Report – Jacking System Assessment” for details on all these items. In this document we will focus on the main considerations coming from the assessment – jacking speed, fatigue life, and the system cost estimate.

When considering the original intention of drilling jack-ups, jacking system speed is not a primary operational concern. Shifting focus to WTIV operations, however, it becomes obvious that jacking speed requires more consideration as it can have a more significant impact on overall operations than for drilling operations. It is therefore necessary to improve jacking speed to accommodate the increased demand on jacking for WTIV operations. For the existing jacking system, the average tested speed at normal jacking loads measured 17.38” per minute jacking up, and 24.00” per minute jacking down. To change speed of the system you must either change the AC power frequency to yield faster jacking speeds or change the gear ratio which requires a major design change of the jacking system design. A gear ratio change is not advised as it would take a significant amount of time and money, while also being a much less certain method of being effective compared to the power frequency change.

Changing the AC power frequency is typically done by using a variable frequency drive (VFD) system. An increase in frequency yields faster jacking speeds that are approximately linear to power frequency when measured in Hertz (Hz). So, for example, the typical power frequency of 60 Hz when doubled to 120 Hz should yield a doubling of speed. VFD systems selected for this are typically able to produce power at both lower and higher frequencies than the normal 60 Hz. From prior studies it has been seen that 5 ft seas offshore in the US Northeast held to have approximately 8 second wave periods, and thus taken as a design condition. At the nominal 60 Hz speed of 17.38” per minute, 13 wave periods will occur before clearing the wave zone. Quadrupling the speed (i.e. 240 Hz) will clear the zone in three wave periods. This is also at 4 times the normal power, but for a very short burst of power lasting on the order of 30 seconds. Examination of available VFD system catalogs indicates that speed ratios from maximum to minimum of well over 10 are not at all uncommon in the power ranges required, and 400 Hz is available at power levels needed at reasonable costs.

Adjusting the speed of the jacking system by adding a VFD system is relatively simple and has added benefits such as being able to move the legs in leg lifting mode much faster, and so be able to time motions of the lowered leg much better with respect to wave motion of the WTIV.

Regarding the fatigue life, this jacking system was originally designed for approximately 14,000 rack-feet of jacking operations on a drilling rig. In general, this system has proven to exceed that measure over the long lives of oilfield rigs. 50- and 60-year-old rigs with this jacking system exist, which worked consistently during that 50- to 60-year life. Thus, in principle, jacking system lifespans of 35,000 feet (50 years) to 42,000 feet (60 years) can be reasonably expected with some repair and replacement being done.

A test stand exercise that ran this type of jacking system (both gears and rack) beyond 100% of a nominal full life was completed, with the rack portion used in the test consisted of eight teeth, measuring just over 8.378 ft in length. In a single jacking event, the jacked length both up and down is 140 ft, yielding an effective ratio of fatigue of rack to gear teeth of approximately 8.355-to-1. This is based on 140 ft / (2*8.378 ft). This life cycle test was 14,168 feet jacked at average loads over the nominal 375 kips. The established 20-year design life was thus proven by this test. Considering 14,000 rack-feet of design life for the jacking gear in this test, this relates to approximately 116,973 rack-feet of fatigue life on the rack. By the end of the test the rack section still functional but had experienced noticeable damage. It should be noted that a jack-up rig uses the legs which are over 300 ft long and jacking loads will be broadly spread over the leg length, greatly reducing the likelihood of damage such as that experienced during the test.

When considering the fatigue life for the WTIV application, it is necessary to understand the principal differences in jacking between a drilling rig and a WTIV. The main difference comes in frequency of jacking. Drilling rigs typically jack-up 4 to 5 times a year while WTIVs typically jack-up 50 to 160 times a year (i.e., one to three times a week to install a new turbine). Given the infrequency of jacking, drilling rigs can therefore wait for good weather, while WTIVs are much more schedule sensitive and therefore must jack-up in a broader range of conditions for the location. This implies usage of the jacking system anywhere from 10 to 40 times more frequently for the WTIV application. Relating this to the 20-year design life for drilling rigs, the 14,000 rack-feet is instead reached in as little as 6 months to two years of life. Assuming an estimated 35,000 rack-feet of life, this is reached in 1.25 to 5 years of life.

Perhaps the most useful way to consider fatigue for the WTIV is to establish the frequency in which the wear on the jacking gears/equipment needs to be inspected in detail and replaced as necessary. A suitable reference point for establishing this frequency can be considered from the aforementioned testing that yielded approximately 117,000 rack-feet of usage, at which point it is reasonable to expect much of the rack would need to be replaced. At a rate of 50 jack-ups per year with the same airgap, load line, and mud allowance as a drilling rig, it would take 16.7 years to reach the 117,000 rack-feet and serious fatigue damage to the rack. Operators would need to do major checks of the jacking gears at least every two years. At a rate of 150 jack-ups per year with the same airgap, load line, and mud allowance, it would take 5.57 years to reach the 117,000 rack-feet and serious fatigue damage to the rack. Operators would need to do major checks of the jacking gears at least every 8 months.

Therefore it would be reasonable to expect for a very “high use” WTIV that major checks and potential repairs may be necessary every 8-12 months. Rack life will be on the order of 117,000 rack-feet at normal to high (375-440 kip) jacking loads. When considering lighter loads (1/3rd or less the normal loads) the load life will extend by a significant margin.

On jacking systems, the most certain way to improve fatigue life is to significantly reduce the load per jacking unit. This will be the most important change in the conversion of a standard drilling jack-up to a WTIV. Implementation of regular inspection and repair of jacking units and guide systems should be followed using existing operating manuals and technical guides to ensure equipment is maintained the in the best possible condition.

Regarding the cost estimate for the system upgrade, each of the five jacking legs on the WTIV will contain four units per row and measure six rows high. The legs will already have a total of four rows per leg in place as part of the drilling rig setup. Jacking units are considered separate from the jack case and jack guides when tallying up the total components to be added for the upgrade.

The existing legs each contain 16 jacking units over four rows of height, for a total of 80 units. Increasing to six total rows per leg for the WTIV will require 40 new jacking units to be installed. This will add a total of 444,600 lb and cost $10,660,000.

For the existing legs as outfitted for the drilling rig application there will be jack cases and guides running vertically to work in conjunction with one jacking unit from each row. Therefore a total of four jack cases and guides are installed on the legs (four units per row) and are suitable for the four rows of height installed on the legs. These existing jack cases and guides each weigh 62,268 lb and would cost approximately $807,217 to fabricate from scratch. In order to meet the WTIV requirements, these cases and guides will need to be modified to be suitable for six rows of height. Doing so will increase the total weight of each to 104,938 lb and would cost roughly $452,042 to complete the modification to the existing components.

The WTIV will require the incorporation of new VFD system (including controls) to allow for faster jacking speeds. Utilizing historical data for VFD systems, both cost and weight of the new system can be scaled to approximate based on the number of jacking units in a system. In this case, the scaled data reflects the addition of 500 lb per jacking unit, along with a cost of $118,063 per unit.

Table 13 outlines the total weight and cost estimate of the upgraded jacking system for the WTIV.

Table 13. Upgraded Jacking System Weight Estimate.

Total weight and cost estimate for the upgraded WTIV jacking system outlined by component.

Component	Weight (lb)	Cost
Repair 80 Existing Jacking Units	889,200	$7,106,667
Add 40 New Jacking Units	444,600	$10,660,000
Extend Jack Cases and Guides	2,098,760	$9,040,820
Incorporate VFD System	60,000	$14,167,500
TOTAL	**3,492,560**	**$40,974,987**

Details of this assessment completed in Phase 3 are found in the Document “D08.01 Report – Jacking System Assessment” and Document “D09.01 Memorandum – Cost Estimate – WTIV”.

5.4 Cost Estimate

A high-level cost estimate of the capital cost to fully convert the WTIV was developed as part of this project. Details for the estimate were developed from several sources, including the following:

- Project Advisor estimations
- Available market data
- EOC historical project data

Specific comments are provided within the cost estimation summary that identifies the source of the estimation. Unless otherwise noted, the cost estimation includes all associated costs with the line item (such as purchase price, installation, integration, etc.).

The complete cost estimate summary is found in Table 14. The overall summary is roughly $360MM.

Table 14. WTIV Cost Estimation.

Summary of the high level WTIV cost estimation (capital costs) to convert the WTIV.

Component	Cost	Comment
Part I - Rig Purchase		
Purchase LeTourneau 116C Jack-Up Rigs, Two (2)	$30,000,000	Market assessment.
Sub-Total, Part I	**$30,000,000**	
Part II - Demolition and Preparation		
General Services - Two (2) Rigs	$2,000,000	Estimation provided by Kiewit Offshore Services (Advisor to EOC for this project)
Quayside mooring, ventilate/gas free tanks - Two (2) Rigs	$1,000,000	
Removal of Drill Packages: derrick, substructure, cantilever, etc. - Two (2) Rigs	$1,000,000	
Shaker House Removals - Two (2) Rigs	$1,500,000	
Removal of the Cement Unit Structure - Two (2) Rigs	$1,400,000	
Removal of the P-Tanks - Two (2) Rigs	$1,400,000	
Removal Aft Jacking Leg and Jackhouse - One (1) Rig	$2,000,000	
Helideck Removal - One (1) Rig	$300,000	
Auxiliary Crane Removals - One (1) from each Rig	$200,000	

Remove Lifeboats - Two (2) from each Rig	$300,000	
Remove Accommodation House - One (1) Rig	$3,300,000	
Refurbish of Accommodation House - One (1) Rig	$10,000,000	
Steel Renewals - Two (2) Rigs, 24 MT each	$4,000,000	
Sub-Total, Part II	**$28,400,000**	
Part III - Fabrication and Installation of New Structure		
Fabrication of Midbody and Transition Pieces	$44,900,000	Estimation provided by Kiewit Offshore Services (Advisor to EOC for this project)
Installation of Midbody and Transition Pieces	$11,300,000	
Fabrication and Installation - Main Crane Pedestal	$400,000	
Fabrication and Installation - Main Crane Boom Rest	$200,000	
Fabrication and Installation - Thruster Foundations - Eight (8)	$2,000,000	EOC historical data
Fabrication and Installation - Interconnect Ballast Piping	$500,000	
Sub-Total, Part III	$59,300,000	
Part IV - Upgrading / Installing On-Board Systems		
Repower of WTIV, including new Switchgear	$6,900,000	Equipment price information from Wartsila
Wartsila 6L32 Generator Sets - Eight (8)	$9,000,000	
Fixed Thrusters WST-24FP - Eight (8)	$48,720,000	
Dynamic Positioning and Control Systems	$375,000	
Machinery Control and Monitoring System	$300,000	
Standard Bridge Equipment	$500,000	
Emergency Generator Set	$500,000	EOC historical data
Repair Existing Jacking Units - Eighty (80)	$7,200,000	Estimation provided by Allrig (Subcontractor to EOC for this project)
Add New Jacking Units - Forty (40)	$10,700,000	
Extend Jack Cases and Guides	$9,100,000	
Incorporate VFD System	$14,200,000	
Huisman PMC-60000-1200 Main Crane	$31,500,000	Estimation provided by Huisman (Advisor to EOC for this project)
Personnel Tower	$5,250,000	EOC historical data
Refurbishment of Existing Auxilliary Cranes - Four (4)	$500,000	
Commissioning of Mechanical Systems	$10,000,000	
Public Alarm / General Alarm System	$500,000	
Fire Fighting and Safety Equipment	$700,000	
New Lifeboats - Two (2)	$1,000,000	
Fast Rescue Boat - One (1)	$225,000	
Sub-Total, Part IV	**$157,170,000**	
Part V - Management, Engineering, and Overhead		
Project Management/Procurement	$2,000,000	EOC historical data
Detailed Engineering	$10,000,000	
Wave Basin and Wind Tunnel Model Testing	$500,000	
Inspection / FAT	$1,000,000	

Site Team	$5,000,000	
Incline Testing after Completion	$600,000	
Construction All Risk Insurance	$8,000,000	
Regulatory Fees	$2,000,000	
Sub-Total, Part IV	**$29,100,000**	
Estimate Summary	**$303,970,000**	
Contingency (10%)	**$30,397,000**	
TOTAL w/ Contingency	**$334,367,000**	
OPTIONS		
Option for Water cushion for landing legs on bottom	$27,000,000	Estimation provided by Allrig (Subcontractor to EOC for this project)
TOTAL W/ OPTION	**$361,367,000**	

5.5 Basis of Design

A finalized version of the Basis of Design for the concept was assembled at the end of the work that provides the most accurate details for the concept upon project conclusion (done as part of Phase 3). This document was titled "D01.02 Memorandum – Basis of Design". A finalized set of Principal Particulars can be found in Table 15

Table 15. Finalized Concept Principal Particulars.

Principal particulars for the WTIV including dimensions, speeds, and regulatory information based on this feasibility concept work.

Principal Particulars	
Length Overall (Including Heliport)	209.3 m
Length Between Perpendiculars	193.9 m
Breadth	61.1 m
Depth	16.8 m
Draft	10.9 m
Maximum Elevated Payload	3,922 tonnes
Maximum Speed	12 knots
Leg Length	145.5 m
Maximum Leg Protrusion	113.1 m below Bottom of Hull
Class	ABS
Flag	USA

5.6 Final Report

This document represents the draft version of the final report for the project, titled "D10.01 Final Report (DRAFT)".

6 Conclusions

The scope of work completed over the duration of the project has yielded positive outcomes for the WTIV concept. No major engineering or design "showstoppers" were encountered, however there are some items that will require continued design and development through further design phases to ensure a fully viable concept.

The main design component that currently remains somewhat open-ended pertains to the longitudinal strength assessment. As noted in Section 5.1, the aft jack-up exhibited overutilizations as part of the assessment. The results could be improved with further removal of existing equipment and supporting structure (i.e., the aft leg well) related to the removed aft leg with the goal of reducing the bending moment load on the aft jack-up. Additionally, reinforcement of the aft jack-up hull is also a possibility, in conjunction with the transition structure, in order to relieve the overutilizations being experienced in the assessment. A more detailed review of the longitudinal strength would be a primary first step in any future design work to ensure that these issues can be dismissed.

Another aspect of the concept that should be further investigated at the start of subsequent design work relates to the drag and power requirements of the WTIV. The speeds estimated as part of this work should be compared against other forms of WTIV vessels to understand how the WTIV transit time measures against these conventional options. It should be noted that speed and transit time are not the only factor, however, as other conventional options may require multiple vessels to interact during the installation process, such as Jones Act barges carrying turbine components, etc. With this in mind, a wholistic view must be considered to understand the overall installation procedure time for a specific number of turbines rather than simply transit speeds.

In terms of other new considerations for the concept that could be explored in future design phases, some ideas include the following:

- Thruster configuration optimization study
    - Shifting thrusters further outwards from the center of the vessel could improve dynamic positioning performance.
    - Potential reduction of thrusters may improve both capital and operational costs.
- Explore the potential to use the WTIV to install turbine foundations.
- Explore the potential to use the WTIV with a "feeder barge" installation method.
- Begin interactions with developers and operators:

- Further understand what they see as the future turbine sizes to be installed.
- Better understand their construction operation plans and how it may affect concept details.