FINAL SYSTEM DESIGN

DELIVERABLE D7.2.9

ADVANCED TIDGEN® POWER SYSTEM

DE:EE0007820

April 30, 2018

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Table of Contents

Purpose

This document presents the final system design completed during Budget Period 1 (BP1) by ORPC and its partners for the Advanced TidGen® Power System Project, DE- EE0007820. The document is excerpted from the Continuation Application submitted by ORPC on April 30, 2018.

From Section 3.2.9 of the Continuation Application: D7.2.9 BP 1 report describing the advanced technology and final system design:

Turbine, Task 1 Advanced Hydrodynamic Design

For a more complete detail analysis of the turbine design, refer to deliverable D1.2: *Technical report with final design, supporting CFD analysis, structural analysis, and development plan* of the Advanced TidGen Power System project.

- **Final Design Overview**

Upon completion of budget period one for task 1 of the Advanced TidGen Power System project, a final turbine design was produced. A model of the final turbine design can be seen in Figure 1.

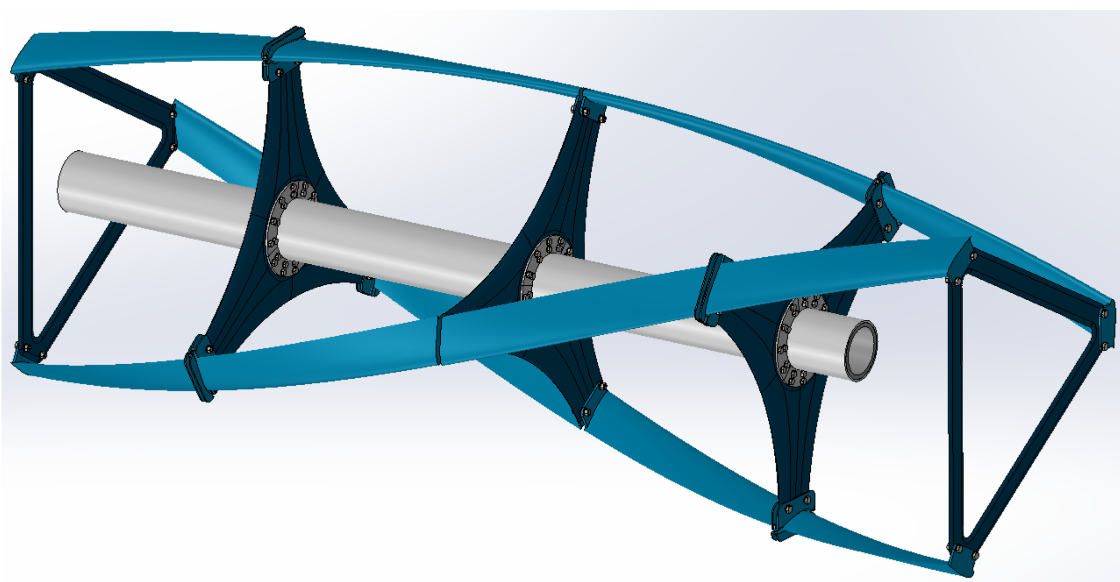


Figure 1: Advanced TidGen Final Turbine Design Model

A detailed description of each component on the turbine is outline in Figure 2. The item image, 1st and 2nd build quantity and a description of the component level design is outlined. The 1st build will consist of building one turbine for evaluation followed by a 2nd build of the remaining seven turbines.

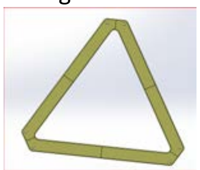
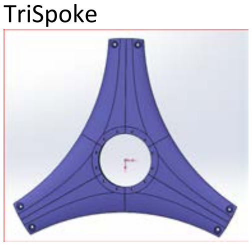
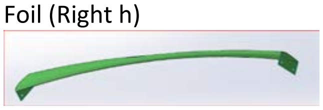
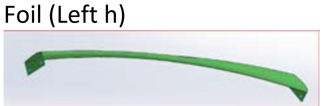
Item	Qty	Description
Triangle 	1st Qty: 2 then 2nd Qty: 14	Approx. weight 28.3 kg each VectorPly, E-QX 6400 (approx. 1.67mm at 50% Volume Fraction(Vf) or equivalent, 12 layers in the main sides, overlap side strips and corner strips, butt layers as needed, having all continuous layers is not possible nor required. 6 Long side strips per side 6 Short side strips per side 6 Corner strips per corner
TriSpoke 	1st Qty: 3 then 2nd Qty: 21	Approx. weight 78.2 kg each VectorPly E-QXM 6410 or equivalent (approx. 1.88mm @ 50% Vf). Overlap where possible, minimizes butted plys, do not stack butted plys without a continuous layer between. Taper as needed. No butted plys should be at the surface (overlaps are ok).
Saddle (Right h) 	1st Qty: 6 then 2nd Qty: 18	Approx. weight 1.7 kg each Alternating layers of (0,90) and (+/-45), 18 oz/sqyd, e-glass (approx. 0.471mm at 50% Vf), 8 pairs of each, 16 layers total. VectorPly E-LT1800 and E-BX1700 or equivalent. Tooled inside and outside.
Saddle (Left h) 	1st Qty: 0 then 2nd Qty: 24	
Foil (Right h) 	1st Qty: 6 then 2nd Qty: 18	Foam core: General Plastics FR7115 or equivalent. Carbon fiber: Zoltek PX35 (0) Uni-Directional Fabric, UD600 or equivalent. Glass fiber: Double bias (+/-45) 18 oz/sqyd, VectorPly E-BX1700 or equivalent. Laminate:13 layers total, 5 glass, 8 carbon, ((+/-45), 0, 0, (+/-45), 0, 0, (+/-45), 0, 0, (+/-45), 0, 0, (+/-45)). Surface veil may be required (TBD). Flanges are a continuation of the upper and lower laminates, terminating 1 carbon from each pair at the foil end, and interleaving 4 layers of ELT-1800. Total flange thickness is 12mm.
Foil (Left h) 	1st Qty: 0 then 2nd Qty: 24	

Figure 2. Turbine components overview with details on component level design details.

This CDR turbine design was produced with project contractor, Blusource Energy Inc., whom ORPC relied on for some design decisions. These decisions included making the foil half the length of the turbine and adding a flange to the ends of each foil section, so the foils could be bolted axially to the struts. The foil section center joint consists of a bolted saddle which clamps the foils to the struts. As seen in Figure 1 the turbine is connected to the shaft by means of a bolted flange that is welded to the shaft. Doubler plates are utilized for this joint.

- **Supporting CFD Analysis**

During the design phase of the turbine development for Task 1 many 2D Computation Fluid Dynamic (CFD) analysis were carried out. Once the turbine was defined during the Critical Design Review (CDR) a final 2D CFD analysis including a buoyancy pod, a representative center nacelle and two counter rotating turbines was conducted. The velocity flow field can be seen interacting with the structure in Figure 2.

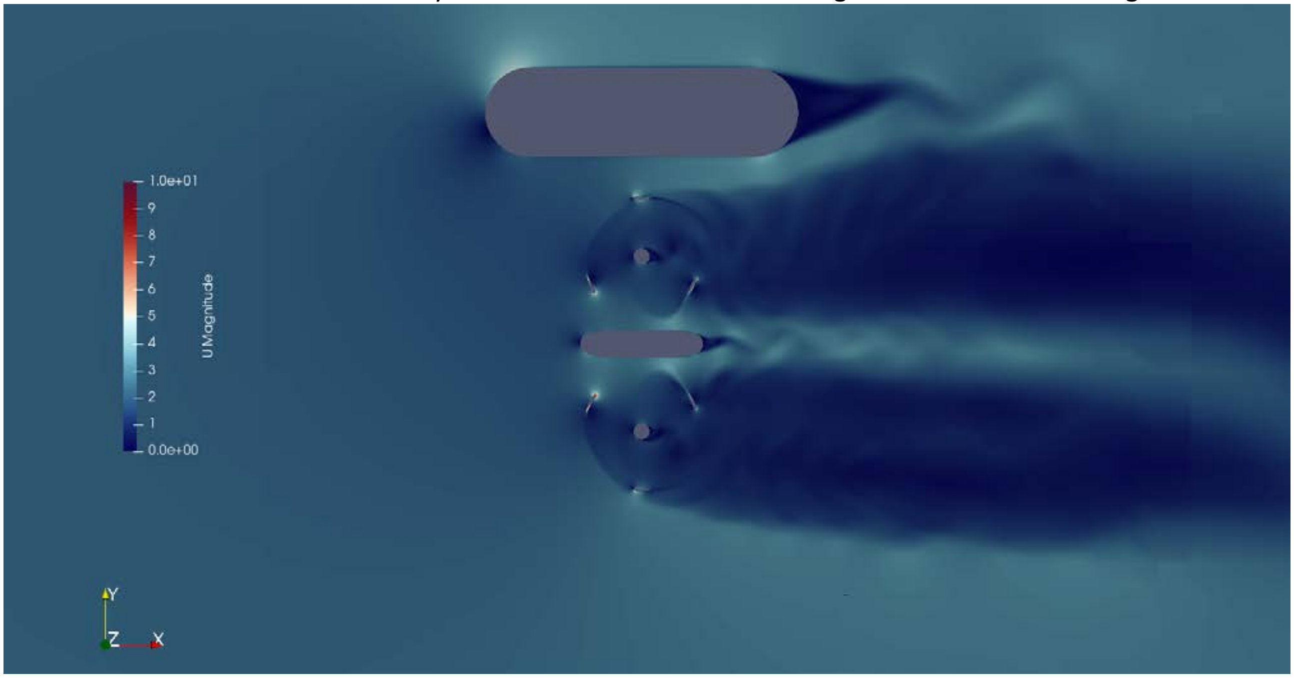


Figure 3. CDR turbine design CFD

The Coefficient of Performance (Cp) vs. Tip Speed Ratio (TSR) curves for the raw 2D data from this CFD analysis is represented graphically in Figure 3. It is interesting to note that the upper and lower rotor have different curves, the lower being a slightly better performer. This is due to the buoyancy pod interfering with the flow field near the upper rotor.

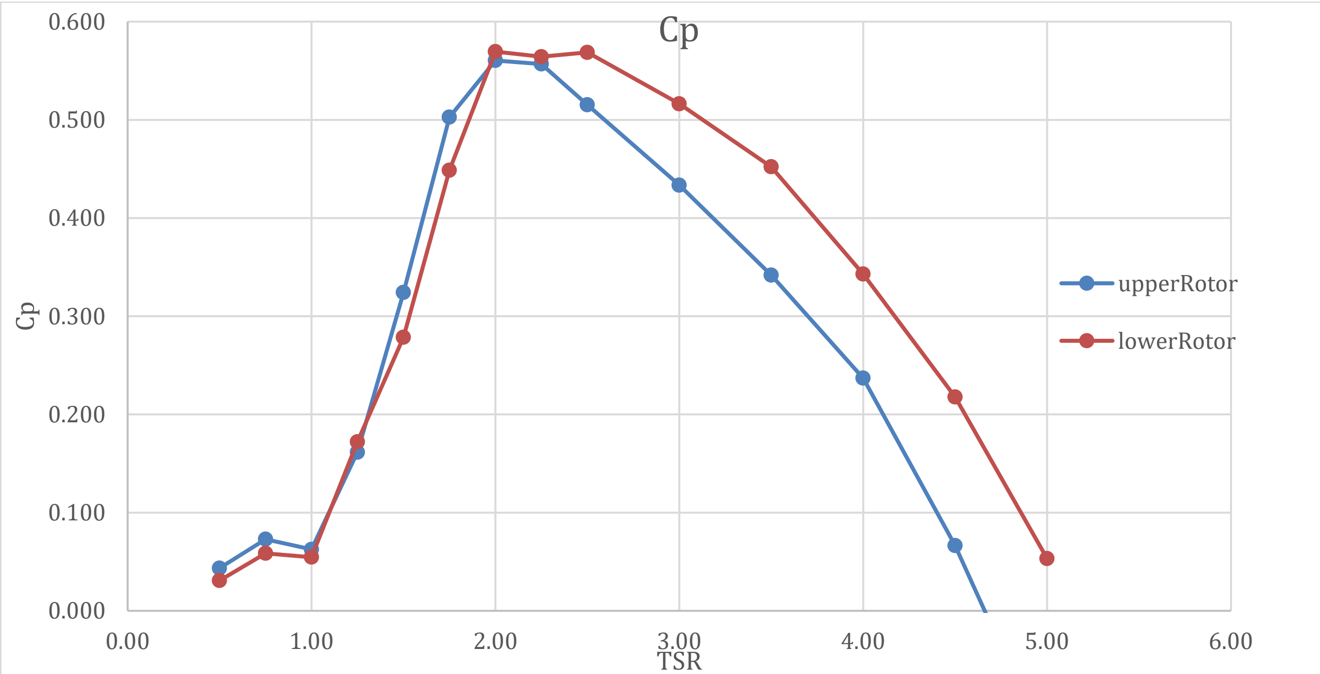


Figure 4. Cp - TSR curve for the raw 2D CFD analysis

ORPC have developed a post processing tool (LExCoSS) to convert 2D CFD into quasi 3D data by extrapolating the 2D loads along the span and helical twist. This process has proven valuable as full 3D CFD analysis is computationally intensive, costly and time consuming. The LExCoSS Cp – TSR curve for the dual rotor case can be seen in Figure 4.

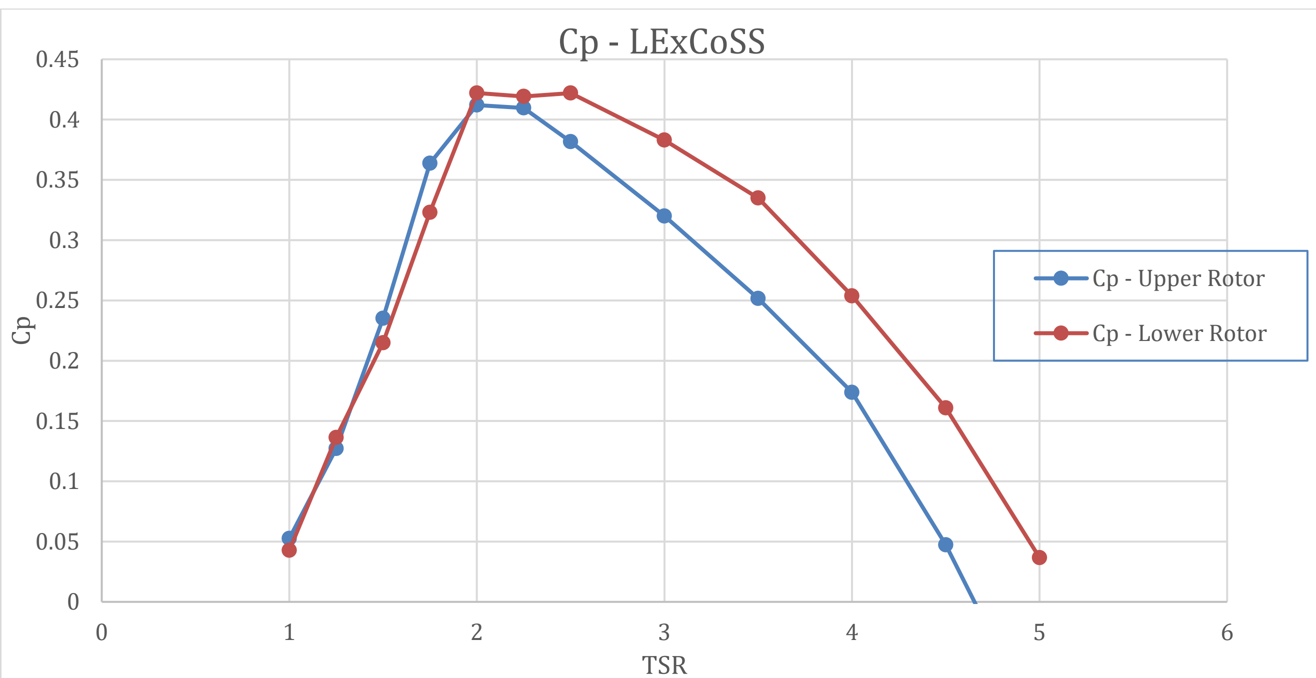


Figure 5. LExCoSS Cp - TSR curve for upper rotor

To conclude, from the raw 2D data the max Cp was 57% which is a high estimate because no loses are accounted for. After the 2D data is post processed with LExCoSS the max Cp drops to an average of 42% which is a reasonable estimate of the final turbine performance and is further verified when compared to the estimate outlined in D1.1 Preliminary turbine hydrodynamic design, which submitted in Q2.

- **Development Plan**

ORPC have engaged manufacturers to quote the turbine build aspect of this project and have received feedback on the manufacturability of the CDR turbine design. Two key areas are targeted for design refinement based on manufacturers input. Firstly, the Foil/Strut joint design.

The joint to connect the foil to the strut has been designed with a bolted saddle connection as seen in Figure 2. It is understood that this design is not hydrodynamically efficient and the manufacturers have suggested a fully adhesive joint that would result in a more reliable high-performance joint. This design can be seen in Figure 6.

Secondly, the cost of incorporating foil profile and chord span wise variation is less than previously anticipated so we can use this to increase the hydrodynamic performance of a turbine. At the tips of the foils the chord can be reduced without altering the structural performance, so it is proposed that the foils will taper to a smaller chord at the foil tips. It is also wise to make the foil profile thicker in the areas of highest strain at the center of the foils. This can be done by tapering the thickness of the foil from a NACA 1524 at the foil center to a NACA 1520 at the tips. This proposed foil modification promises to increase both the structural and hydrodynamic performance.

Along with turbine design refinement, ORPC also intends to perform barge testing of a single turbine for many reasons.

1) Hydrodynamic performance predictions.
   ORPC is aware that CFD analysis are not validated with performance measurements so it is important to characterize the turbine performance with a subsystem test of a single turbine. This testing will give a realistic Cp - TSR curve that can be used to accurately calculate Annual Energy Production (AEP) and Levelized Cost of Energy (LCOE).
2) Turbine Load Predictions.
   To-date all the loads applied to the turbines are calculated with 2D CFD and are anticipated to be conservative. For this reason, ORPC intend to measure the turbine loads and use that information to refine the affected components of the system, namely the mooring system. The Advanced TidGen Power System uses a buoyant tension mooring system with large gravity anchors which prove to be a challenging engineering problem. The updated turbine loads will allow ORPC to design an appropriately sized anchor and buoyancy pod reducing cost and deployment difficulty.
3) Turbine Durability. As part of BP2, ORPC will work with CERL and the turbine manufacturer for preliminary structural testing of the turbine joints, and more complete evaluation during accelerated life testing as part of Task 8.

- **Conclusion**

At present ORPC have a turbine as defined during the CDR which after engaging manufactures many design refinements have been suggested which ORPC intend to implement. Figure 6 shows a model of a turbine with some of the proposed design changes. Also, from initial input from manufacturers, this turbine is expected to be cheaper than the CDR turbine design due to less manufactured parts and simplified design.

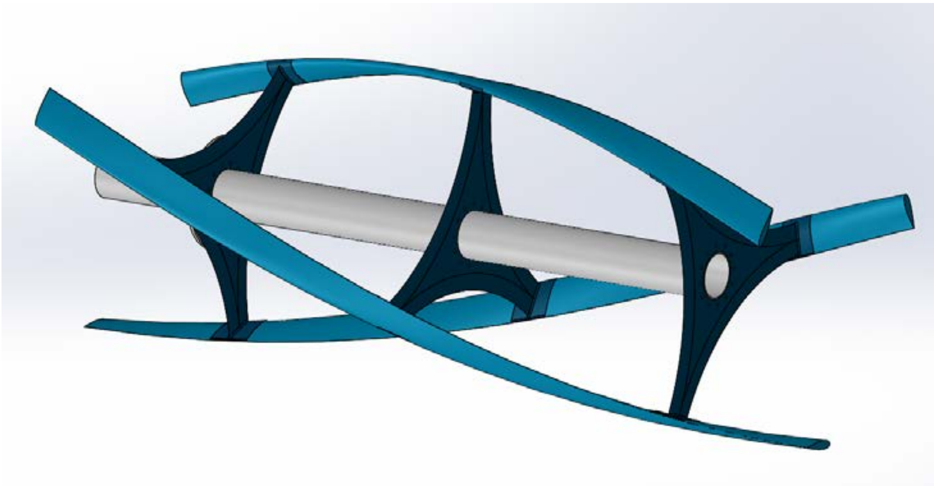


Figure 6: Advanced TidGen Turbine design improvements

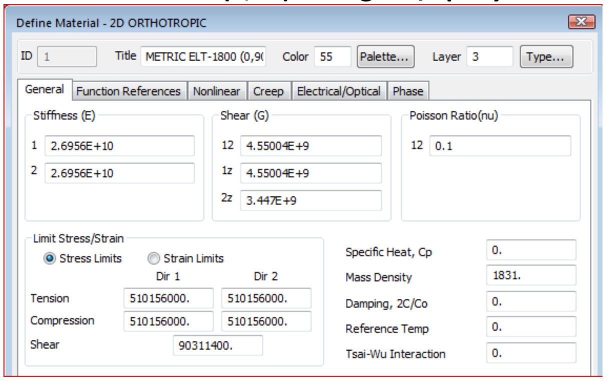
Turbine, Task 2 Composite Optimization for Durability

ORPC worked with three partners, CERL, MSU and BluSource Energy, to develop the turbines for the Advanced TidGen® system. This work was done in parallel with the effort in Task 1, and as stated above, ORPC has engaged potential manufacturers for design refinement towards cost reduction and better structural performance based on improved manufacturing quality and joint strength.

D-TD20-10146, Deliverable D2.3 Technical Report on the Characterization Program, summarizes the effort for material selection, static and fatigue testing performed at MSU, and early characterization of failure modes and failure mechanisms.

The following overviews the composite design as produced for the Critical Design Review (CDR). The composite layup was designed by Blusource Energy Inc. and consists of +/- 45 E-Glass interlayered with two layers of unidirectional carbon fiber. The biaxial E-glass transmits shear loads on the foil while the unidirectional carbon adds stiffness to limit deflections and strains. The material properties and laminate schedule for the FEA model are shown in Figure 18 and Figure 19.

METRIC ELT-1800 (0,90) Fiberglass/Epoxy



METRIC Unidirectional Carbon Uni Hexply 600 34%

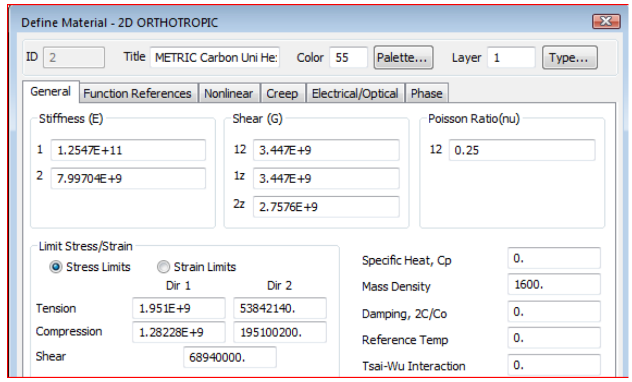


Figure 18: Composite Material properties for E-Glass and Carbon fiber used for the CDR composite structural design of the turbine.

Foil Layup @ 8.89mm

Layup Editor

ID 2 Title METRIC Foil Laminate

Global Ply ID (optional) AutoCreate Material

0..None

--- Top of Layup --- Total Thickness = 0.008892

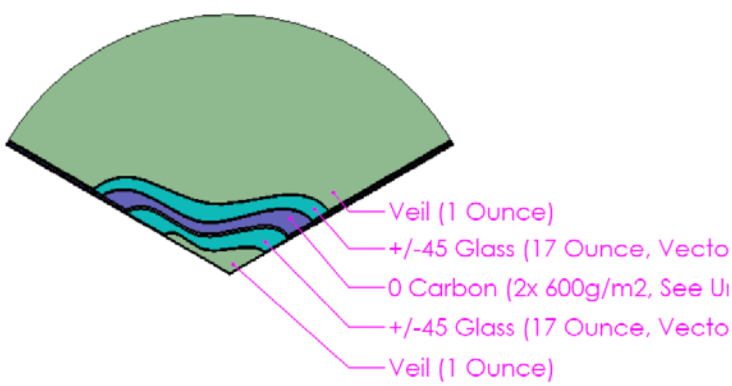
Ply ID	G...	Material	Thickness	Angle
16		5..METRIC ELT-1800 (0,9...	0.000457	45.
15		6..METRIC Carbon Uni He...	0.000615	0.
14		6..METRIC Carbon Uni He...	0.000615	0.
13		5..METRIC ELT-1800 (0,9...	0.000457	45.
12		6..METRIC Carbon Uni He...	0.000615	0.
11		6..METRIC Carbon Uni He...	0.000615	0.
10		5..METRIC ELT-1800 (0,9...	0.000457	45.
9		6..METRIC Carbon Uni He...	0.000615	0.
8		6..METRIC Carbon Uni He...	0.000615	0.
7		5..METRIC ELT-1800 (0,9...	0.000457	45.
6		6..METRIC Carbon Uni He...	0.000615	0.
5		6..METRIC Carbon Uni He...	0.000615	0.
4		5..METRIC ELT-1800 (0,9...	0.000457	45.
3		6..METRIC Carbon Uni He...	0.000615	0.
2		6..METRIC Carbon Uni He...	0.000615	0.
1		5..METRIC ELT-1800 (0,9...	0.000457	45.

--- Bottom of Layup ---

Laminate Equivalent Properties

16 Plies - Total Thickness = 0.008892

In-Plane Properties
Ex = 9.1317E+10 Ey = 1.1347E+10 Gxy = 6.1624E+9
NUxy = 0.39771 NUyx = 0.0494182
Alphax = -1.3474E-7 Alphay = 7.25038E-6 Alphaxy = 0.
Bending/Flexural Properties
Exb = 8.23E+10 Eyb = 1.2174E+10 Gxyb = 6.87501E+9
NUxyb = 0.4226 NUyxb = 0.0625132
Alphaxb = -1.5425E-7 Alphayb = 5.94709E-6 Alphaxyb = 0.



TriSpoke Laminate @ 12 mm

Layup Editor

ID 1 Title METRIC ELT-1800 (0,90) glass

Global Ply ID (optional) AutoCreate Material

0..None

--- Top of Layup --- Total Thickness = 0.012704

Ply ID	G	Material	Thickness
16		4..METRIC ELT-1800 (0,90) glass	0.000794
15		4..METRIC ELT-1800 (0,90) glass	0.000794
14		4..METRIC ELT-1800 (0,90) glass	0.000794
13		4..METRIC ELT-1800 (0,90) glass	0.000794
12		4..METRIC ELT-1800 (0,90) glass	0.000794
11		4..METRIC ELT-1800 (0,90) glass	0.000794
10		4..METRIC ELT-1800 (0,90) glass	0.000794
9		4..METRIC ELT-1800 (0,90) glass	0.000794
8		4..METRIC ELT-1800 (0,90) glass	0.000794
7		4..METRIC ELT-1800 (0,90) glass	0.000794
6		4..METRIC ELT-1800 (0,90) glass	0.000794
5		4..METRIC ELT-1800 (0,90) glass	0.000794
4		4..METRIC ELT-1800 (0,90) glass	0.000794
3		4..METRIC ELT-1800 (0,90) glass	0.000794
2		4..METRIC ELT-1800 (0,90) glass	0.000794
1		4..METRIC ELT-1800 (0,90) glass	0.000794

--- Bottom of Layup ---

Laminate Equivalent Properties

16 Plies - Total Thickness = 0.012704

In-Plane Properties
Ex = 2.1528E+10 Ey = 2.1528E+10
Gxy = 8.40138E+9
NUxy = 0.281225 NUyx = 0.281225
Alphax = 0. Alphay = 0. Alphaxy = 0.
Bending/Flexural Properties
Exb = 2.2678E+10 Eyb = 2.2678E+10
Gxyb = 7.67926E+9
NUxyb = 0.242833 NUyxb = 0.242833
Alphaxb = 0. Alphayb = 0. Alphaxyb = 0.

Figure 19. Foil laminate schedule used for the CDR composite structural design of the turbine.

Product of the turbine will incorporate process control measures developed as part of Task 2. The figure below illustrates the fabrication process for the composite turbine.

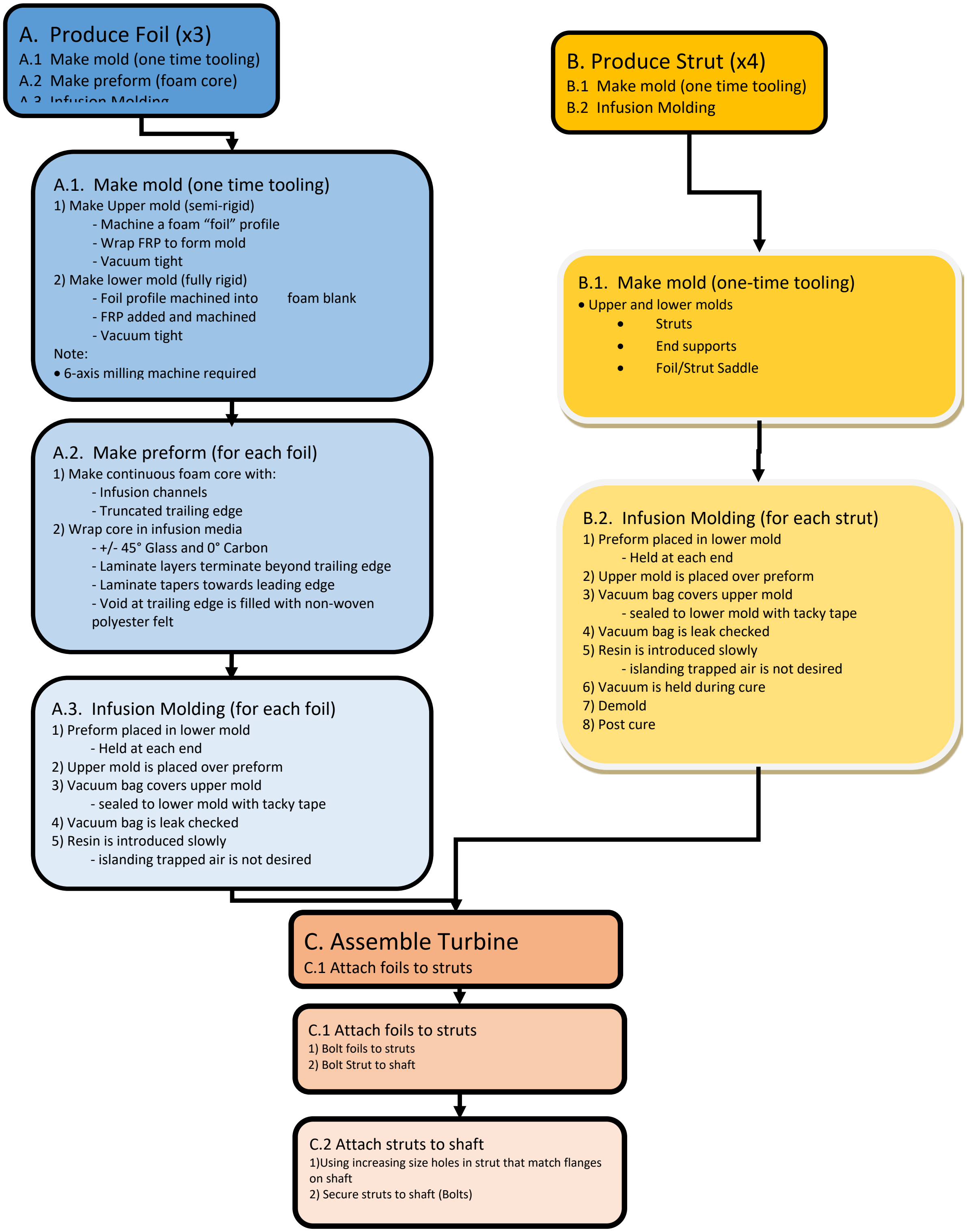


Figure 20. Process map for production of the Advanced TidGen® turbines.

Task 3 and Task 7, System Design

TidGen® System Overview:

The TidGen® System is comprised of four major subsystems: the TidGen® Device (MEC), the buoyant tension mooring system (BTMS), the power and data (P&D) cables, and the onshore power electronics substation.

The TidGen® device consists of an upper and lower turbine generator unit (TGU) comprised of four cross flow turbines and a permanent magnet generator connected via a mechanical driveline. The TGU are held in place by a structural chassis and lateral buoyancy pod. The buoyancy pod provides enough buoyancy for the system to operate suspended in the water column while being held beneath the water surface by a tension mooring system.

This device has an overall net buoyancy of 980kN (630kN with mooring lines and bridle weight), which when combined with predicted device drag, results in a maximum lay-down angle of 57^{o} in the maximum drag condition of turbine freewheel in 3.5 m/s (Figure 18). The total estimated dry weight of the full device is 140,000 kg, with overall dimensions of 34.7m long (cross stream), 8.2m height, and 8.8m length (streamwise) (Figure 19).

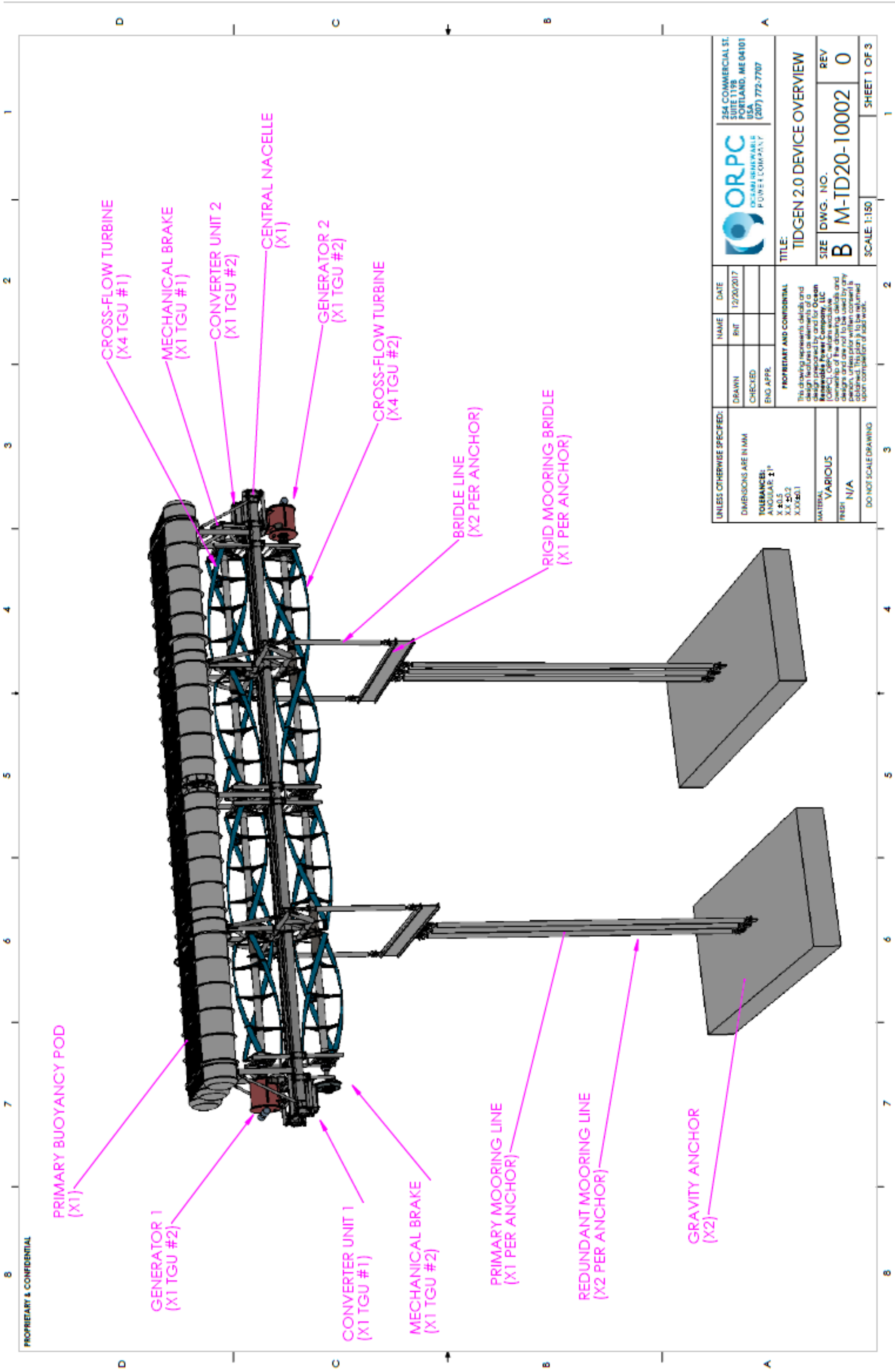


Figure 21: TidGen System Overview (not including P&D cables or shore station)

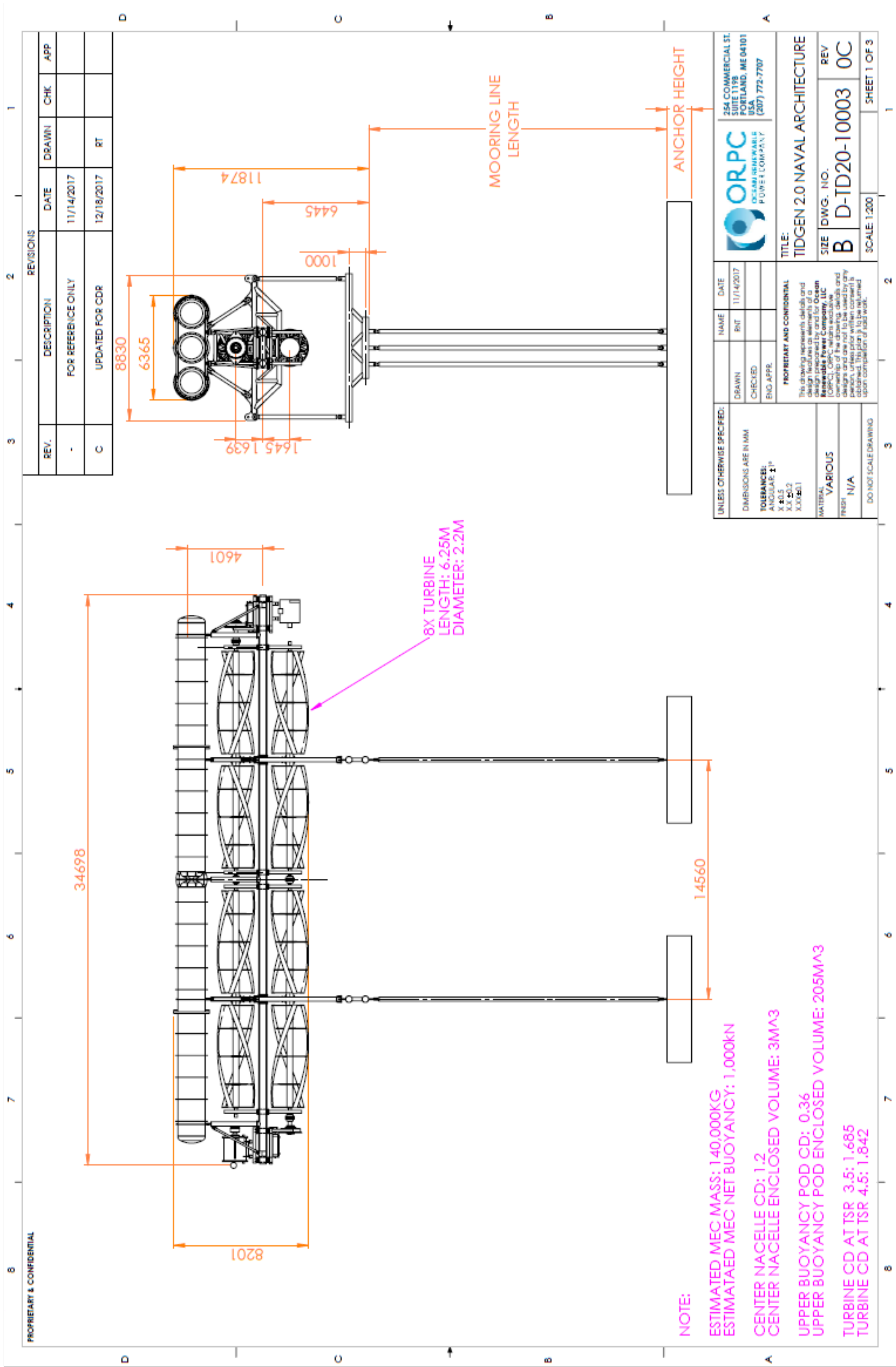


Figure 22: TidGen System Device Dimensions

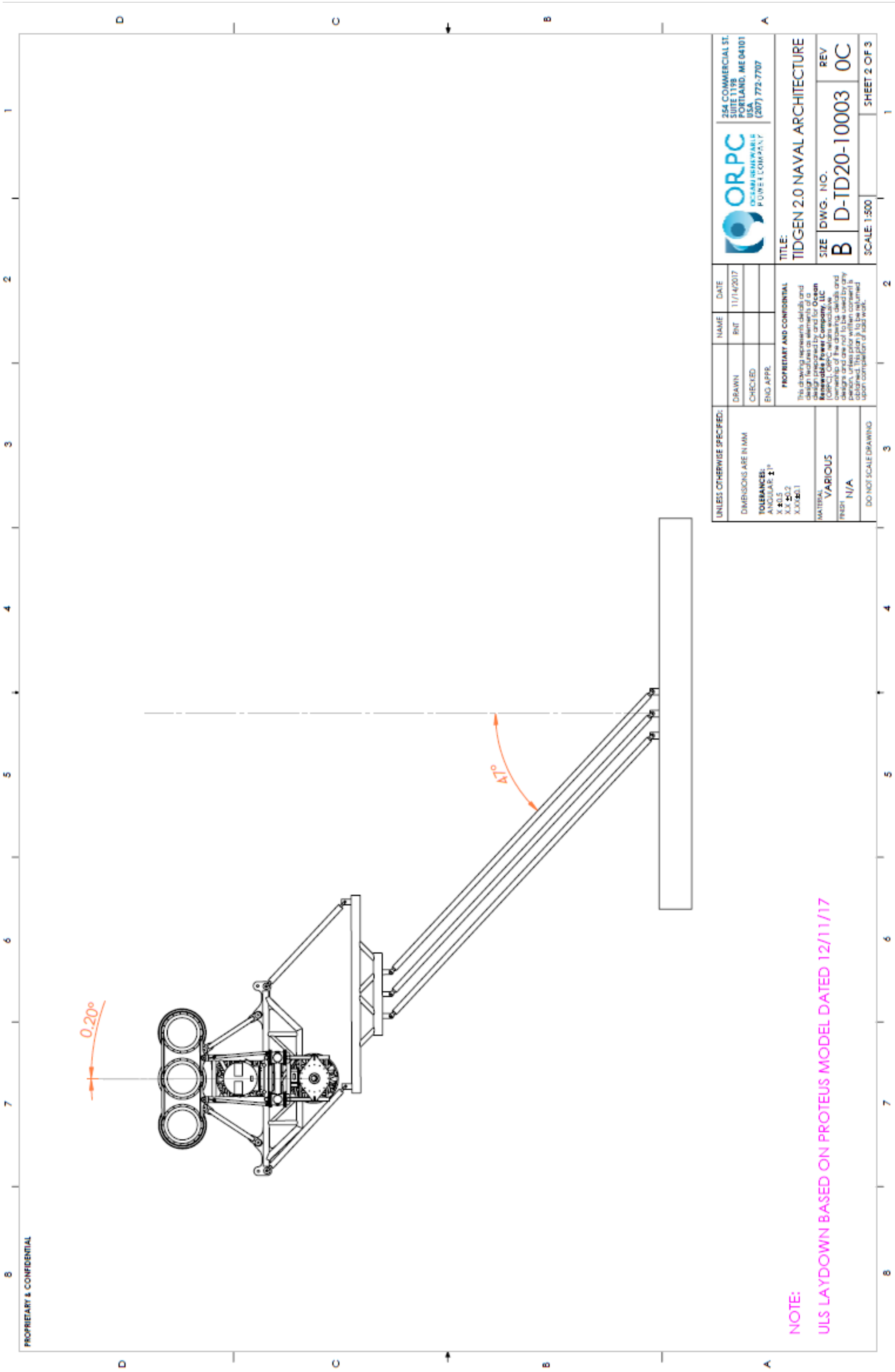


Figure 23. TidGen Device Laydown during peak flow

Table 7 provides an overview of the critical specifications for the TidGen® Power System as of the CDR.

Table 7. TidGen 2.0 Critical System Specifications

Specification	Value
Type	
Turbine Type	Cross flow
Turbine Location	Mid-water column
Foundation Type	Buoyant Tension Mooring System
Anchor Type	Gravity (site dependent)
Power Output	
Rated Power to grid	200kW (assuming 2km transmission)
Max Power to grid	
Power Type at Grid	3 Phase AC; 277/480 VAC; 60Hz (based on grid requirements)
Subsea Power Transmission	1000VDC
Operating Environment	
Environment	Marine
Flow direction	Bi-directional off-axis flow up to +/- 20º in max flow speed
Maximum operational flow speed	3.5m/s (including turbulence)
Rated current speed	2.25m/s
Survivable current speed	4.0m/s
Minimum operating depth	18m (at mean lower low water)
Maximum operating depth	40m (at mean higher high water)
Minimum bottom (anchor) depth	TBD during development testing
Maximum bottom (anchor) depth	N/A
Data and power transmission length	up to 5km
Bottom Type	varied
In-Water temperature range	0deg C to 20deg C
Out of Water temperature range	-40deg C to 45deg C
Weighs & Measures	
Maximum Device dimensions	34.6m (L) x 9.0m (H) x 6.3m (W)
Device weight (not including mooring system)	140,000kg
Maximum component (shipping) weight	10,000kg
Maximum component (shipping) dimensions	16m (L), 2.5m (w), 2.59m (h)
Anchor weight	Site dependent
Reliability	
System design life	20 year (in water)
Routine Inspection Frequency	Annual
Routine Maintenance Frequency	5 year
System Operations & Monitoring	Remote monitoring & automated health monitoring safety checks
Design Standards & Certification	DNV-GL standards (DNVGL-ST-0164);
System Availability	94%
Local Asset Requirements	

Maximum required lifting equipment	20T crane (metric ton)
Marine vessel power limit	TBD during development testing, Hp (total net power)
Technical expertise for on-site assembly and maintenance	Not required
Transportation	
Required mode	Standard flatbed trailer

Design Load Cases (DLC) Overview:
As part of the overall design effort critical load cases were determined following DNV guidelines, development of concept of operations, and preliminary failure modes and effect analysis (FMEA).

Table 8. Primary Design Load Cases for the TidGen 2.0

ConOps Phase	DLC	Operating Condition	TSR	Design Condition	Current Condition		Primary Load Types (source/detail)
					Vel	Dir	
1. Subsystem fabrication QA/QC Shipping	1.1	Component lifting	N/A	ULS	N/A	N/A	G (gravity)
	1.2	Component Shipping	N/A	ULS	N/A	N/A	G (gravity)
2. Subsystem Integration	2.1	Device Assembly	N/A	ULS	N/A	N/A	G (gravity)
3. Deployment	3.1	Mooring System Installation	N/A	ULS	0.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	3.2	P&D Cable Installation	N/A	ULS	0.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	3.3	Device Installation to Water	N/A	ULS	0.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	3.4	Device Re-orientation	N/A	ULS	0.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	3.5	Device Towing	N/A	ULS	0.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	3.6	Device Installation	N/A	ULS	0.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
5. Normal Operation	5.1	Peak Power Production	2.0	ULS, FLS	2.25 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	5.2	Torque-limited Power Production	3.0	ULS, FLS	3.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	5.3	One row freewheel, one row braked**	4.5 / 0.0	ULSa	3.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	5.4	One row freewheel, one row Torque limited**	4.5 / 3.0	ULSa	3.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	5.5	Both rows in freewheel	4.5 / 4.5	ULSa	3.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
	5.6	Fully Braked Turbines	0.0	ALS	4.0 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure) ††
	5.7	Startup – single row†	0.0 – 3.0	ULS, FLS	3.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure) Q (historical test data – transient load peaks)

	5.8	Startup – all turbines	0.0 – 3.0	ULS, FLS	3.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure) Q (historical test data – transient load peaks)
	5.9	Shutdown – single row†	0.0 – 3.0	ULS, FLS	3.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure) Q (historical test data – transient load peaks)
	5.10	Shutdown – all turbines	0.0 – 3.0	ULS, FLS	3.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure) Q (historical test data – transient load peaks)
	5.11	Debris impact	3.0	ALS	3.5m/s	Determine acceptable debris impact limits/tolerances for subsystems	
	5.12	Single Mooring line failure	3.0	ALS	3.5m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure) Q (historical test data – transient load peaks)
	5.13	Single connection pin failure	3.0	ALS	3.5m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure) Q (historical test data – transient load peaks)
7. Routine 5yr Maintenance	7.1	Device Removal	N/A	ULS	0.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)
8. System Decom. & Removal	8.1	Mooring System Removal	N/A	ULS	0.5 m/s	0°/180°, 15°	E (CFD, DNV-RP-H103) G (buoyancy, gravity, hydrostatic pressure)

** Both bottom row freewheel and top row in freewheel must be considered.

† This includes 4 variants: top row startup/shut-down with bottom row braked, top row startup/shut-down with bottom row in torque-limited power production, bottom row startup/shut-down with top row braked, and bottom row startup/shut-down with top row in torque limited power production.

††During a severe weather event, the increased wave height needs to be considered. This may affect both flows around the device and the hydrostatic pressure experienced by the device.

Turbine Load Overview:
A primary aspect of system loadings is the hydrodynamic lift, drag, and axial loads generated by the turbines. In many cases these loads represent the highest loads experienced by the TidGen® system. The determination of TidGen® loads was primarily developed through the use of computational fluid dynamics (CFD). Table 9 shows the primary design coefficients for the TidGen® turbine. See *D-TD20-10009 - TidGen 2.0 Turbine Design Loads*.

Table 9. TidGen Turbine Load Coefficients. See D-TD20-10009

TSR	***Cp***	***CD***	***CL***
0.50	0.111	0.595	-0.165
0.75	0.228	0.640	-0.230
1.00	0.423	0.841	-0.276
1.25	0.545	0.981	-0.339
1.50	0.612	1.074	-0.308
1.75	0.655	1.187	-0.289
2.00	0.677	1.292	-0.272
2.25	0.681	1.385	-0.256
2.50	0.663	1.462	-0.242
3.00	0.580	1.583	-0.219
3.50	0.451	1.685	-0.199
4.00	0.270	1.763	-0.211
4.50	0.040	1.842	-0.218

Characteristic Velocity Profile*:*
To enable device designs independent of specific site velocity characteristics, a generic "characteristic" velocity profile was developed for the TidGen® system design. This velocity curve utilized scaled harmonic coefficients and added random turbulence such that the resulting velocity distribution was conservative when compared to measured data from multiple ORPC sites. Velocity distributions for long range site forecasts were developed from using harmonic constituents derived from site data. These distributions were also compared to the characteristic velocity distribution. See *D-TD20-10013 Harmonic Analysis (Utide) and Characteristic Velocity Curve*.

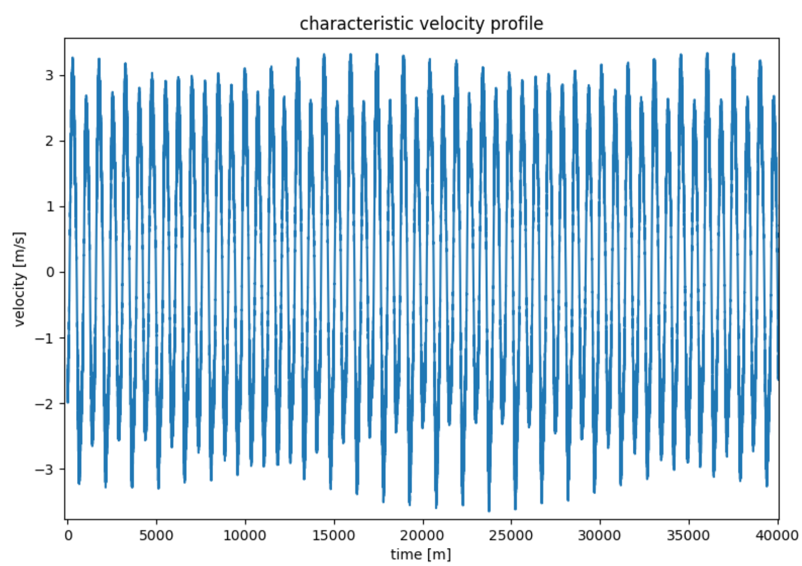


Figure 23. Characteristic design tidal profile

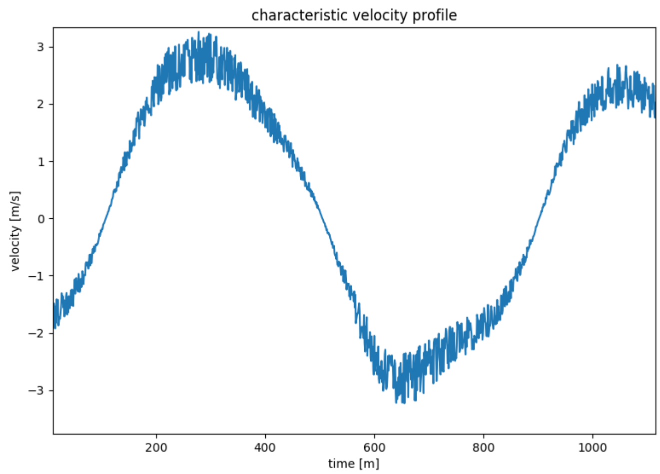


Figure 24. Characteristic velocity profile turbulence

Driveline Design
Refinement of driveline components, analysis tools, and methodology has continued. The focus of recent efforts has been to finalize design, determine costs, and ensure final designs meet performance and cost goals. A critical design review was performed to review all components, a summary is discussed below.

A thorough fatigue analysis was performed on all driveline components to ensure adequate strength and suitability for purpose, utilizing DNV-GL standards. The analysis required full system FEA modeling to establish limits of deflection and derive anticipated loading through system flexure, operational loading, and typical manufacturing tolerances. The current driveline design was determined to be adequate and able to withstand continuous operational loads for the life of the device. Interconnection of turbine sections require flexible couplings for transfer of torque from discrete driveline sections. System flexure for driveline tolerances, both angular and concentric, was reviewed for suitability of chosen couplings and deemed to be acceptable.

The generator to drivetrain connection requires a large, keyless shaft coupling. A suitable solution was found that integrates a flexible coupling, keyless shaft coupling, and a methodology for ensuring corrosion protection for the life of the connection device.

Results from the PTO driveline testing empirically derived misalignment limits of deflection for bearings and overall system flexure. Further analysis was performed on the overall system to determine flexure and misalignment during operation. An unexpected outcome of this review was determination of non-symmetrical system deformation that posed issues for bearing alignment and performance.

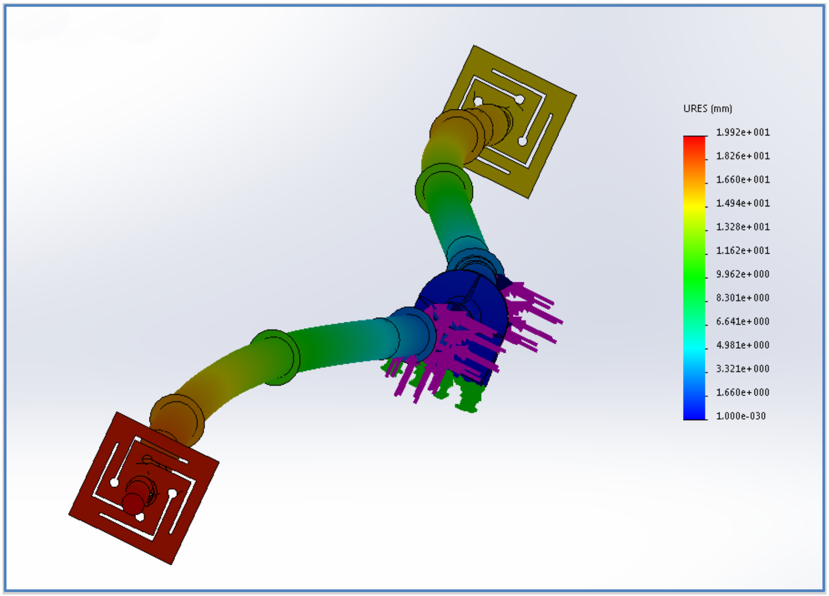


Figure 25. Non-Symmetrical Driveline Deflection

The PTO test assumed symmetrical deflection and the driveline design effort also assumed this attribute, the design requires symmetrical loading to function properly. Modifications are necessary to accommodate non-symmetrical flexure. Specifically, the mid-bearing housing would exceed alignment capabilities with non-symmetrical loading. A modification of the original design will allow for a self-aligning capability of the bearings, in a similar concept to the end stanchions, and reduce the potential for edge-loading and damage to the PCD bearings. The radial bearings are suspended in an elastomer ring and will align with the flexure of the shaft to eliminate edge loading.

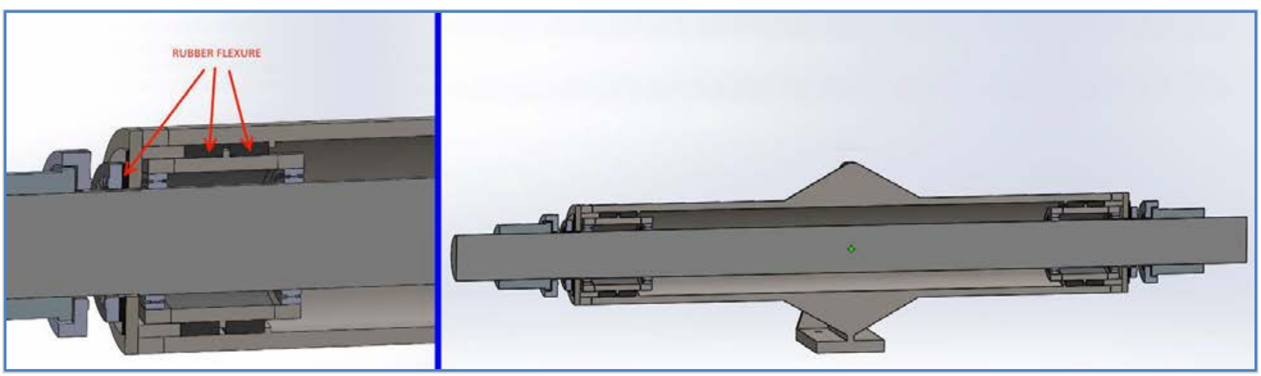


Figure 26. Updated Mid-Stanchion Flexure Assembly

The suitability of flexible couplings for interconnection of drivetrain components was reviewed for suitability of chosen components. The generator to drivetrain connection requires a large, keyless shaft coupling. A suitable solution was found that integrates a flexible coupling, keyless shaft coupling, and a methodology for ensuring corrosion protection for the life of the device.

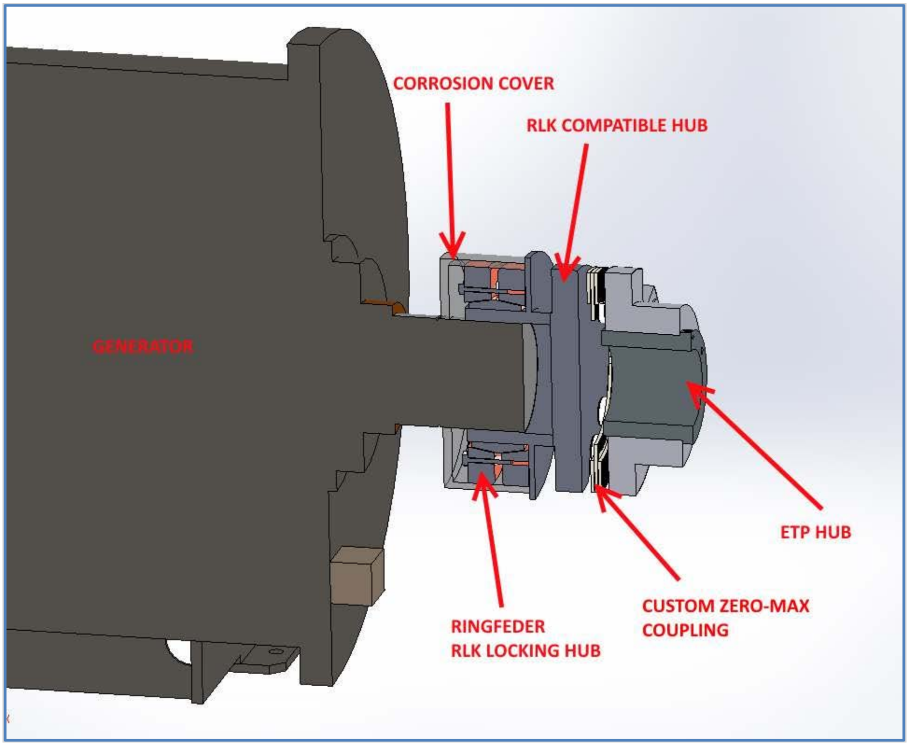


Figure 27. Generator to Driveline Coupling Design

Buoyancy Pod Design

<u>*Design Overview:*</u>

The primary buoyancy pod is comprised of six main buoyancy chambers, each of which was designed following <u>*DNVGL-RP-202 Buckling Strength of Shells*</u> and includes ring stiffeners to prevent buckling. These buoyancy chambers are connected to one another via bolted flange connections and are faired to reduce drag by corregated fairing plate which minimizes weight while maximizing tolerance to hydrodynamic pressure variations (Figure 28). The Buoyancy pod sections are connected to the structural chassis by three sets of pinned connections.

Following the PDR, the buoyancy pod was increased in length to provide additional structural support and stiffness. Although this increased the overall weight of the buoyancy pod, it allowed for significant reductions in the size and weight of the central nacelle, resulting in a decrease in structural weight while simultanously increasing stiffness.

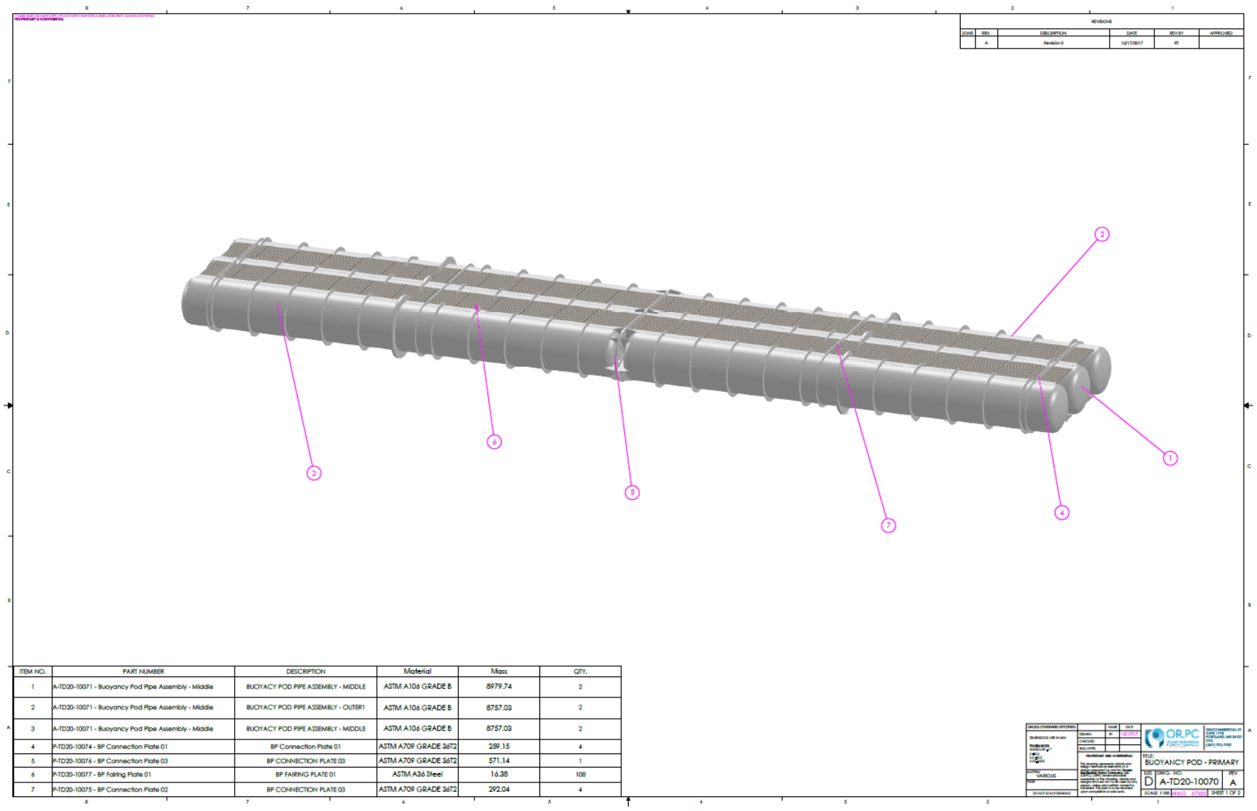


Figure 28. Buoyancy Pod Overview

Analysis Overview:

The main structural pods were desgined following *DNVGL-RP-202 Buckling Strength of Shells*. Considering that external pressure and bending momements (due to buoyancy and structural forces) are the main forces acting on the buoyancy pod, shell buckling and panel ring buckling are considered the primary buckling modes for design. The result of this analysis was to include ring stiffeners along the length of the main tubes along with heavy ring stiffeners near the center of each tube to maintain the cylindrical shape and avoid buckling. Following the PDR, ellipsoidal heads were determined to be preferrable to stiffened plates as they greatly reduce localized stresses. These heads were designed using ASME's Boiler and Pressure Vessel Code.

Combined chassis and buoyancy pod strucutral analysis was conducted using finite element analysis (FEA) (see Chassis Design Analysis). Reaction and connection loads from the full system FEA were utilized in performing detailed FEA analysis at critcal connection joints (Figure 29, Figure 30).

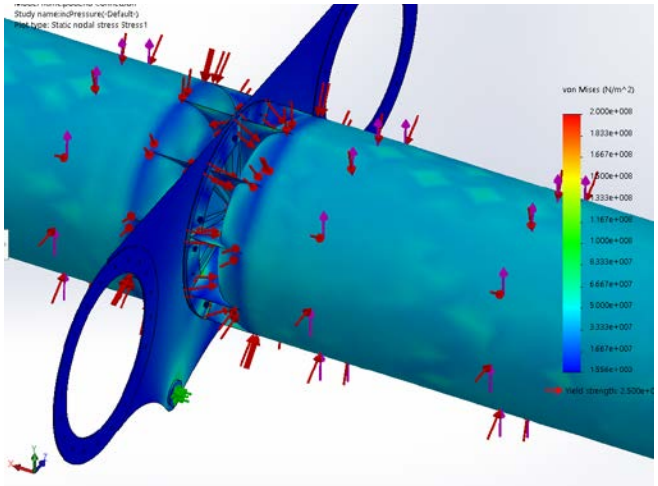


Figure 29. FEA of pod-to-pod end connections under combined operational loading

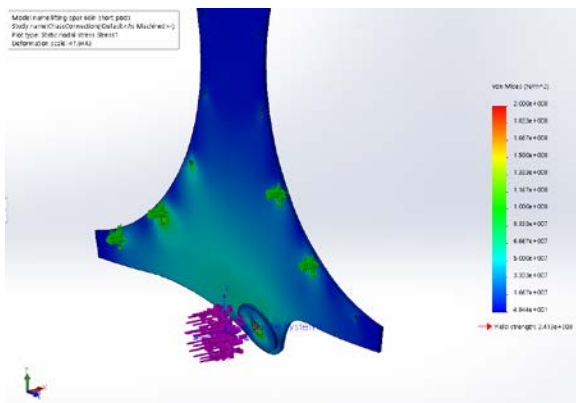


Figure 30. FEA of pod-to-chassis connection under peak operational loads

Structural analysis of the fairing plate was conducted by applying an assumed hydrodynamic pressure load from the turbines to the plate.

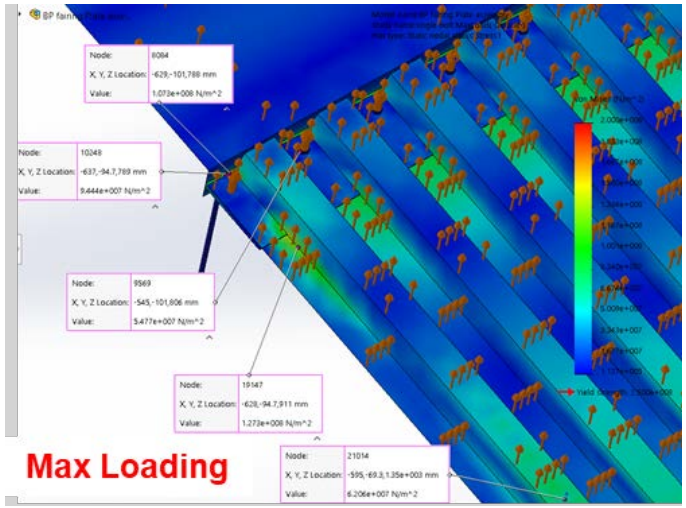


Figure 31. Buoyancy pod fairing plate under maximum hydrodynamic loading

Because the loads throughout the structure will fluctuate with turbine rotations, fatigue analysis was conducted following *DNV-RP-C203 Fatigue Design of Offshore Structures*. Allowable stress ranges for "high risk" aspects of the buoyancy pod design (joints, connections, etc.) were determined based on DNV-RP-203 and assuming high cycle fatigue. These allowable stresses were then compared to the stress ranges resulting from FEA.

Along with analysis of deployed operations, FEA was conducted on the buoyancy pod under assembly loads (Figure 32).

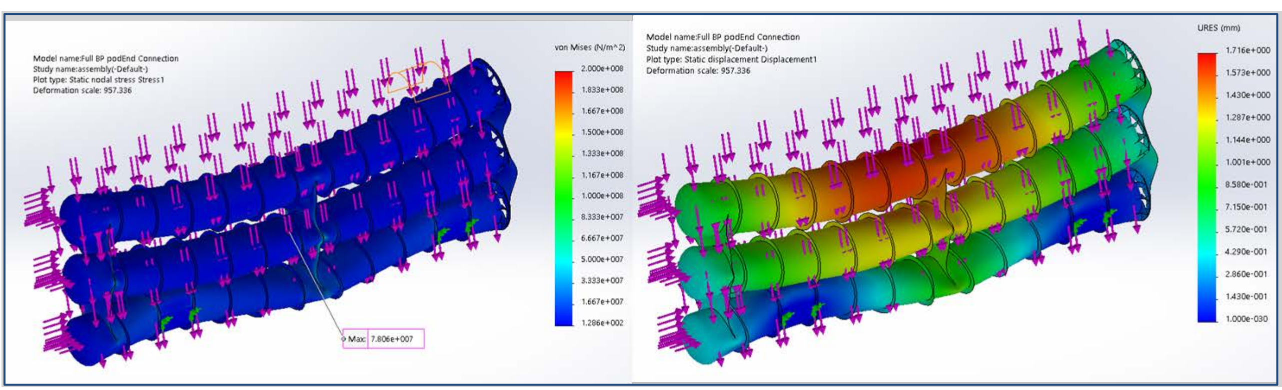


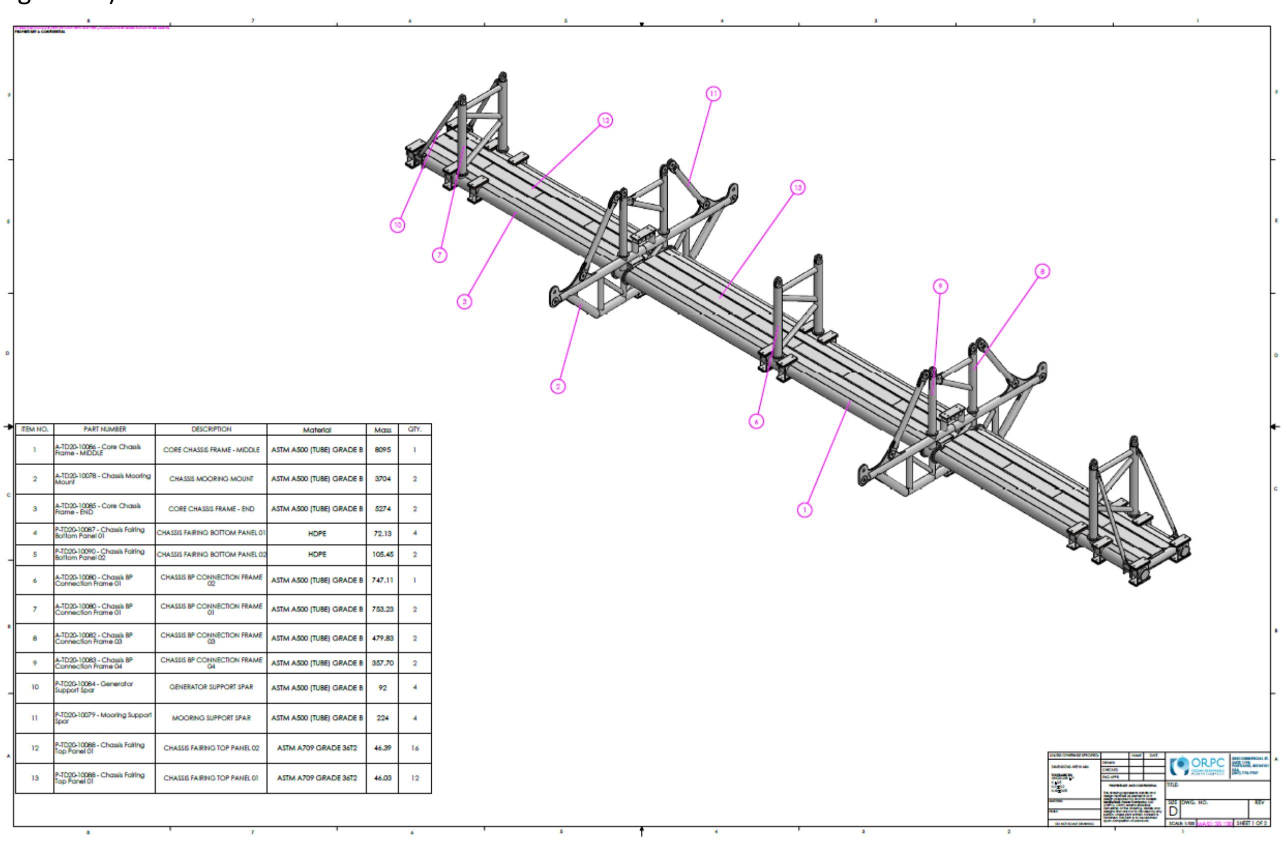
Figure 32. FEA Stress (left) and total deflection (right) of Buoyancy Pod under assembly loads

Structural Chassis Design

<u>*Design Overview:*</u>

The primary role of the structural chassis during deployed operations is to hold the power take off system in position while providing the structural interface between the mooring system and the buoyancy pod. In order to minimize weight while maximizing stiffness, a truss frame is utilized as the primary structural backbone. This frame is segmented into shippable sections, which are connected by bolted flanges, and is covered with a fairing shell cover to improve the flow through the turbines (Figure

33). The main driveline supports, generator, and mechanical brake / converter assemblies, are connected to the chassis through pre-aligned bolted Chockfast interfaces (Figure 34). While the chassis' interfaces with the buoyancy pod and mooring systems are comprised of pinned connections (Figure 35, Figure 36).



ITEM NO.	PART NUMBER	DESCRIPTION	Material	Mass	QTY.
1	A-TD20-10086 - Core Chassis Frame - MIDDLE	CORE CHASSIS FRAME - MIDDLE	ASTM A500 (TUBE) GRADE B	8095	1
2	A-TD20-10078 - Chassis Mooring Mount	CHASSIS MOORING MOUNT	ASTM A500 (TUBE) GRADE B	3704	2
3	A-TD20-10085 - Core Chassis Frame - END	CORE CHASSIS FRAME - END	ASTM A500 (TUBE) GRADE B	5274	2
4	P-TD20-10087 - Chassis Fairing Bottom Panel 01	CHASSIS FAIRING BOTTOM PANEL 01	HDPE	72.13	4
5	P-TD20-10090 - Chassis Fairing Bottom Panel 02	CHASSIS FAIRING BOTTOM PANEL 02	HDPE	105.45	2
6	A-TD20-10080 - Chassis BP Connection Frame 01	CHASSIS BP CONNECTION FRAME 02	ASTM A500 (TUBE) GRADE B	747.11	1
7	A-TD20-10080 - Chassis BP Connection Frame 01	CHASSIS BP CONNECTION FRAME 01	ASTM A500 (TUBE) GRADE B	753.23	2
8	A-TD20-10082 - Chassis BP Connection Frame 03	CHASSIS BP CONNECTION FRAME 03	ASTM A500 (TUBE) GRADE B	479.83	2
9	A-TD20-10083 - Chassis BP Connection Frame 04	CHASSIS BP CONNECTION FRAME 04	ASTM A500 (TUBE) GRADE B	357.70	2
10	P-TD20-10084 - Generator Support Spar	GENERATOR SUPPORT SPAR	ASTM A500 (TUBE) GRADE B	92	4
11	P-TD20-10079 - Mooring Support Spar	MOORING SUPPORT SPAR	ASTM A500 (TUBE) GRADE B	224	4
12	P-TD20-10088 - Chassis Fairing Top Panel 01	CHASSIS FAIRING TOP PANEL 02	ASTM A709 GRADE 36T2	46.39	16
13	P-TD20-10088 - Chassis Fairing Top Panel 01	CHASSIS FAIRING TOP PANEL 01	ASTM A709 GRADE 36T2	46.03	12

Figure 33. TidGen structural Chassis Overview

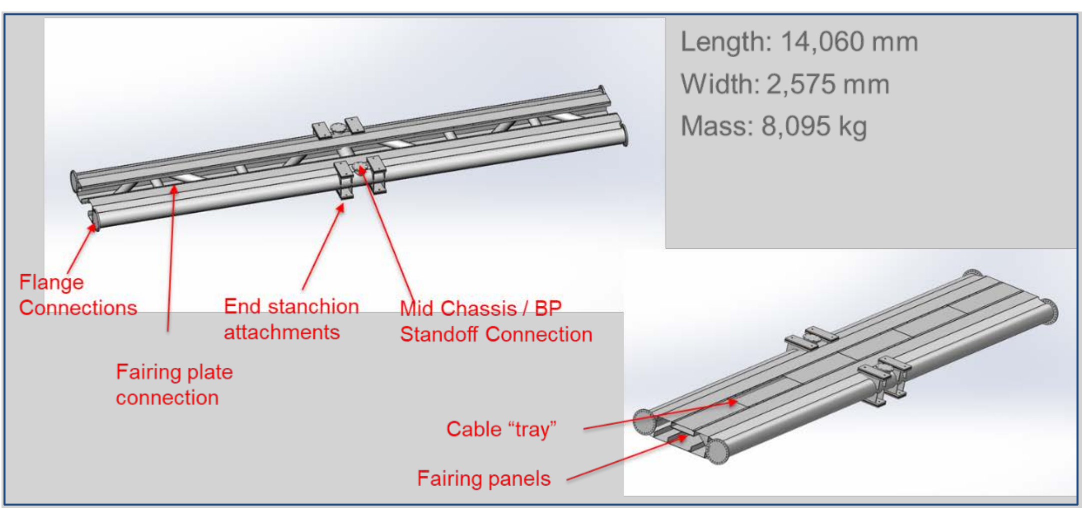


Figure 34. Example of main chassis section

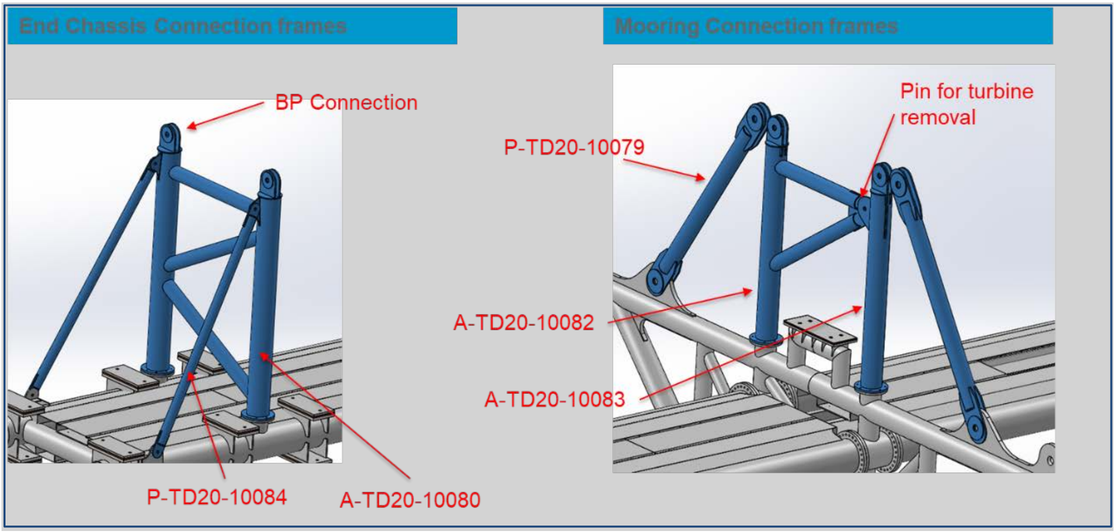


Figure 35. Example Chassis / Buoyancy Pod Connection Frames

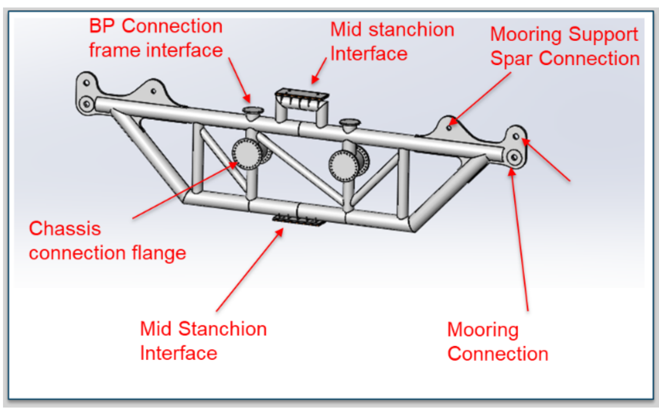


Figure 36. Mooring Connection Spar Overview

Analysis Overview:

Preliminary structural design was conducted using simplified truss models (Figure 37) and ASIC Steel Construction Manual Vol. 14. Following the PDR, a combined structural assembly (half) model was developed for FEA (Figure 38, Figure 39). This model was used to analyze operational design load cases 5.1 – 5.13 (Table 10). As part of this model, connection and reaction loads were determined for each major pin connection for each design load case. These loads were then used as the basis for more detailed component analysis. In addition, chassis deflections at the driveline interfaces were determined. These deflections were an important consideration in the design of the mechanical driveline.

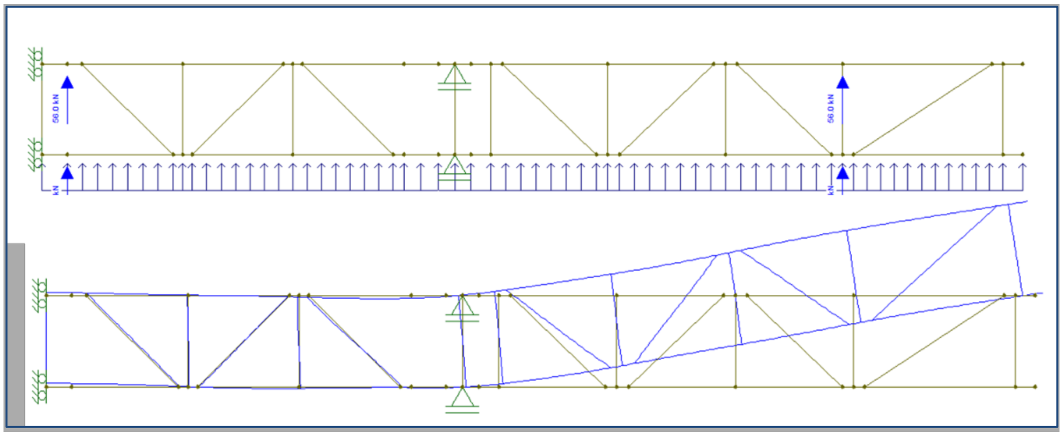


Figure 7: 2D Truss analysis of the main chassis

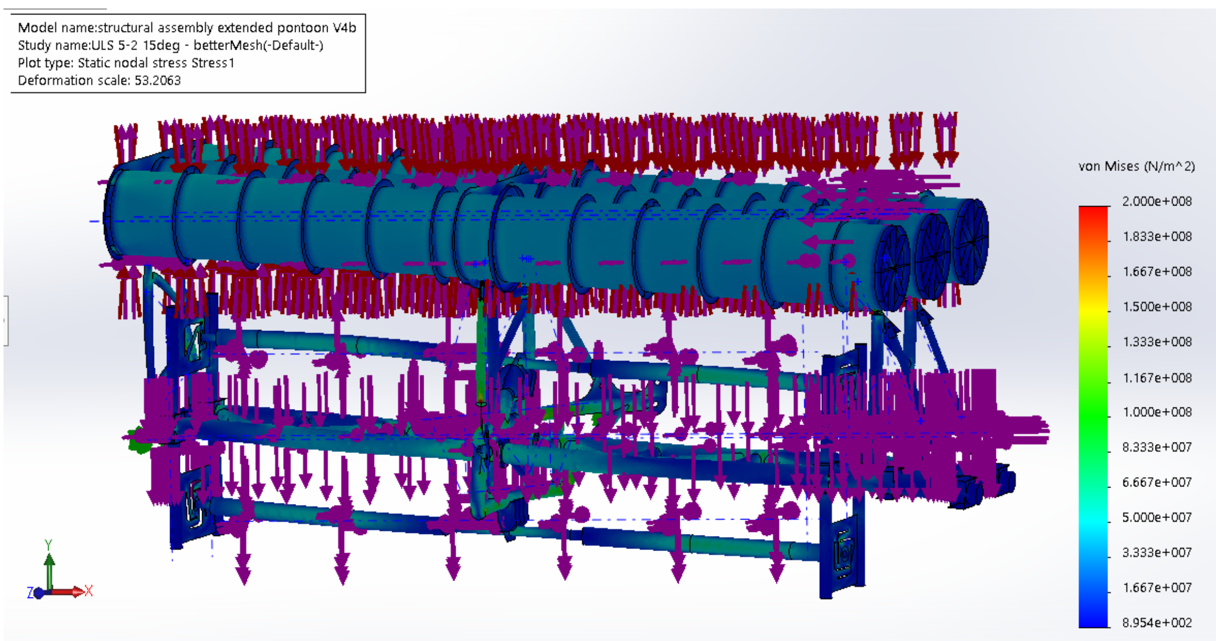


Figure 38. Full (half) structural assembly model FEA Stresses (under DLC 5.2 - 15deg Loads)

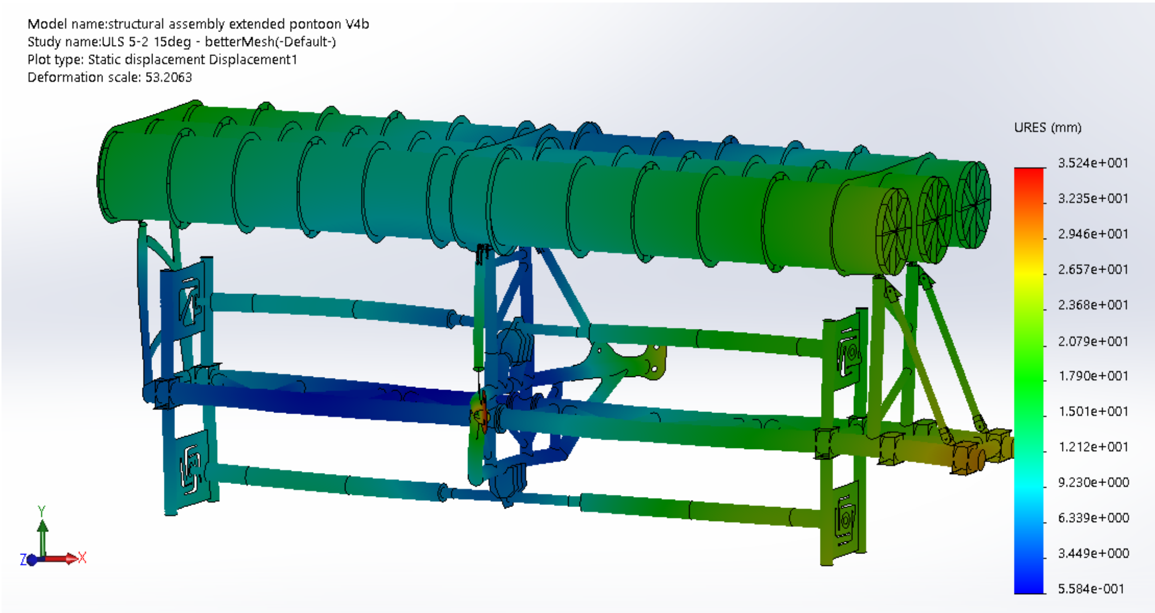


Figure 39. Full (half) structural assembly model FEA Deflections (under DLC 5.2 - 15deg Loads)

Using the local loads determined through the combined structural model, detailed analysis of critical chassis design features was conducted. As with the buoyancy pod, FEA was used to determine maximum stresses under bot ULS and FLS loading states. *DNV-RP-C203 Fatigue Design of Offshore Structures* was utilized to determine the maximum allowable stress ranges for “high risk” aspects each design feature. The FEA stresses were then compared to allowable fatigue values (Figure 40).

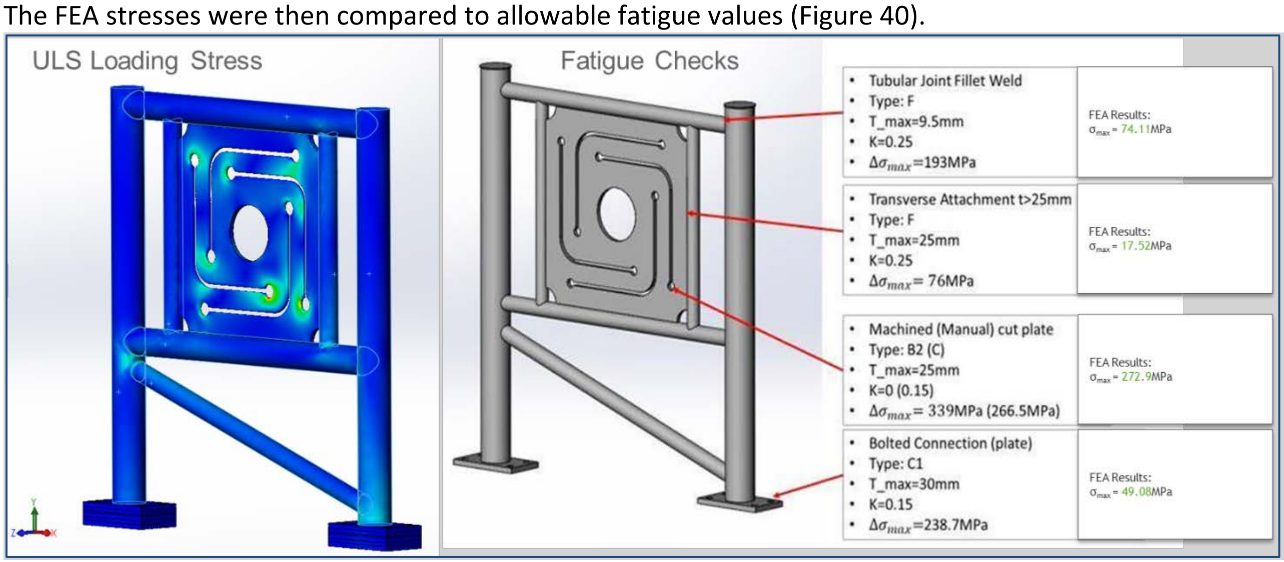


Figure 40. Example FEA stress under ULS loading (left) and corresponding fatigue checks under FLS loadings (right)

Because the chassis is comprised of long slender tubular sections under external pressure, bucking checks were also conducted for those elements where buckling was a concern. For the main tubular sections, conservative estimates for the maximum bending moment were used along with external pressure loads and *DNV-RP-C202 Buckling Strength of Shells* to compare the buckling strength against buckling stresses.

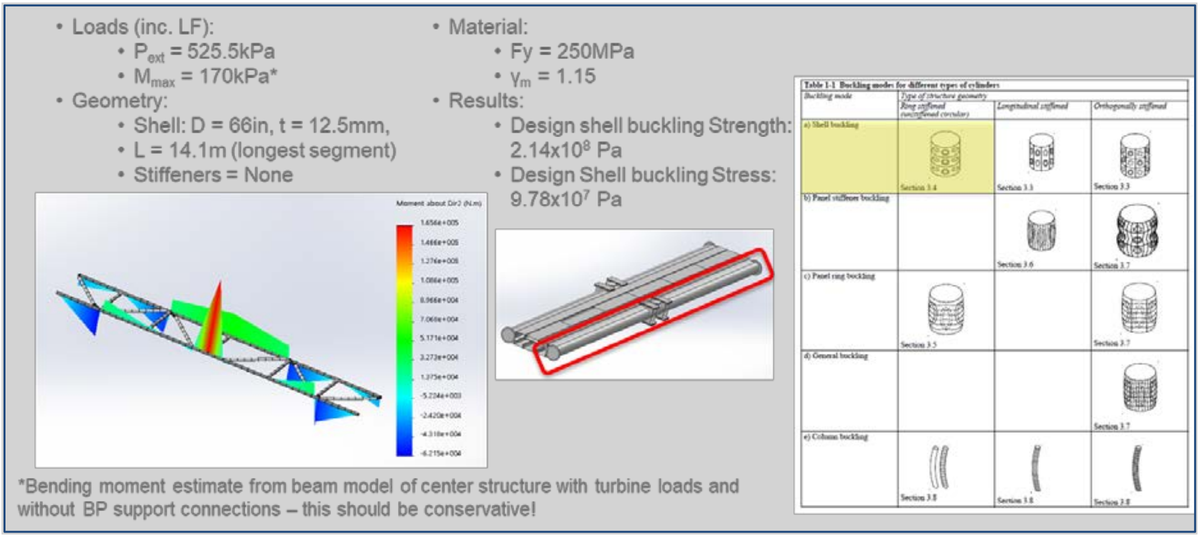


Figure 41. Buckling check for main structural tubes using DNV-RP-C202 Buckling Strength of Shells

Similar buckling checks were performed for any Buoyancy Pod / Chassis connection tube which was determined to be under compressive loading during operations. In all cases, buckling was not found to be a primary concern.

Along with the major structural members, the fairing shell panels were analyzed for maximum stress and deflection under ULS loading, for plate buckling (using *DNV-RP-C201 Buckling Strength of Plated Structures*) and fatigue failure under a varying pressure load due to turbine rotation.

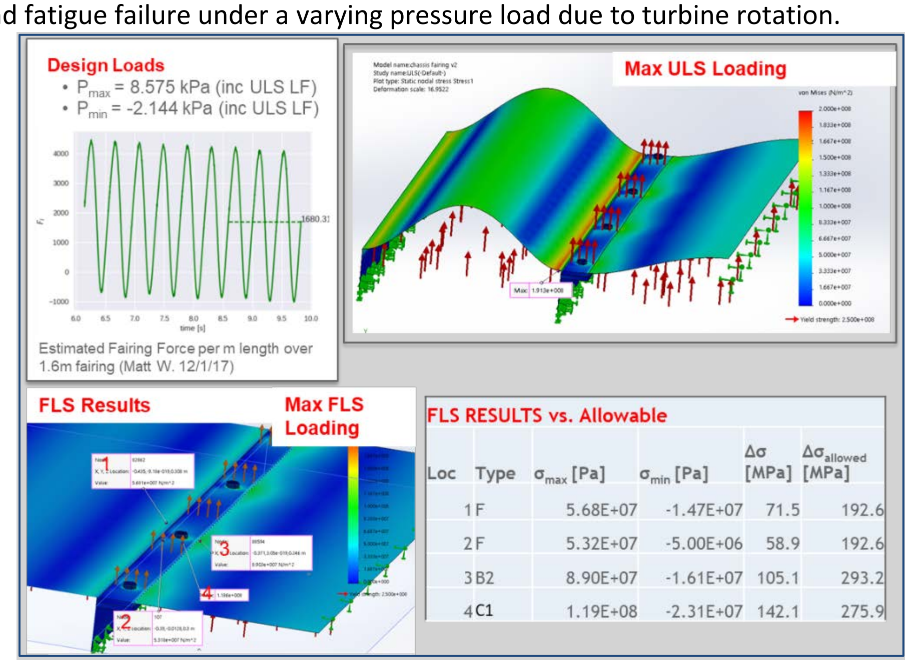


Figure 42. Example Analysis of fairing plate under ULS and FLS conditions using CFD calculated turbine pressure load variations

Assembly conditions were also checked using FEA with assumed assembly loads. The chassis was analyzed under conservative loading conditions which assumed the generator weight was not supported by a separate assembly jig and considered loadings that would maximize structural twist. Under these loading conditions, the structural chassis was found to have minimal deflections and acceptable maximum localized stresses (43).

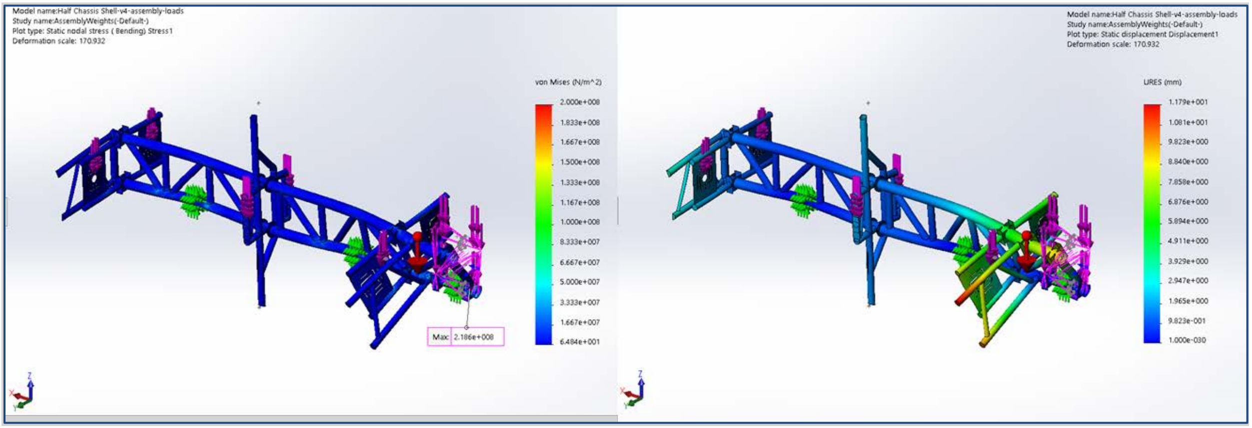
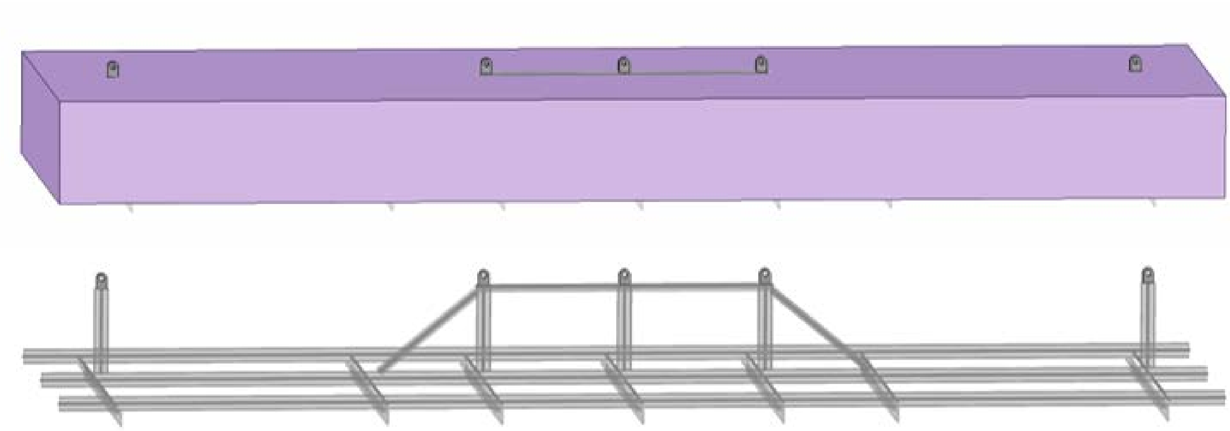


Figure 43. FEA of the chassis under conservative assembly loadings. Chassis Stress (left) and deflection (right)

Mooring System Design

The mooring system is comprised of five major components:

1. Bridle lines that connect the device to the rigid bridle. The principle purpose of the bridle lines is to attach the moorings close to the center of drag while not interfering with turbines or driveline components.
2. A rigid bridle that connects a pair of bridle lines to a primary mooring line and a pair of redundant mooring lines.
3. A primary mooring line that serves as a single point connection from the anchors to the rigid bridle. During normal operations all load is through the primary mooring line.
4. A pair of redundant mooring lines of equivalent size of the primary line however are left in an unloaded state. Should the primary mooring line fail, the redundant mooring lines take up the load preventing loss or significant damage to the device.
5. Gravity anchor, they serve to hold the device in place through the primary mooring line.



Anchor Weight	2,400kN
Length	17.2m
Width	7.5m
Height	1.5m

Figure 44. Preliminary gravity anchor design

Of the mooring components, only the gravity anchor is lacking a formal design, a preliminary design is shown in Figure 45. The design of the anchor is highly specific to the bottom type at a specific site to ensure that an anchor is made to the right shape to prevent failing the soil and causing the anchor to sink and be unrecoverable. Second, the underside of a gravity anchor is typically outfitted with shear keys to add holding power, however some geotechnical work is required to ensure the keys are sized appropriately. Third, as currently design the anchors are significantly heavy due to the large drag loads on the system, it is suspected that the turbine drag is not as large as predicted in CFD however testing is required to verify. Therefore, final sizing of the anchors is delayed until verification of turbine loads is performed in the hope that the size of the anchors can be safely reduced.

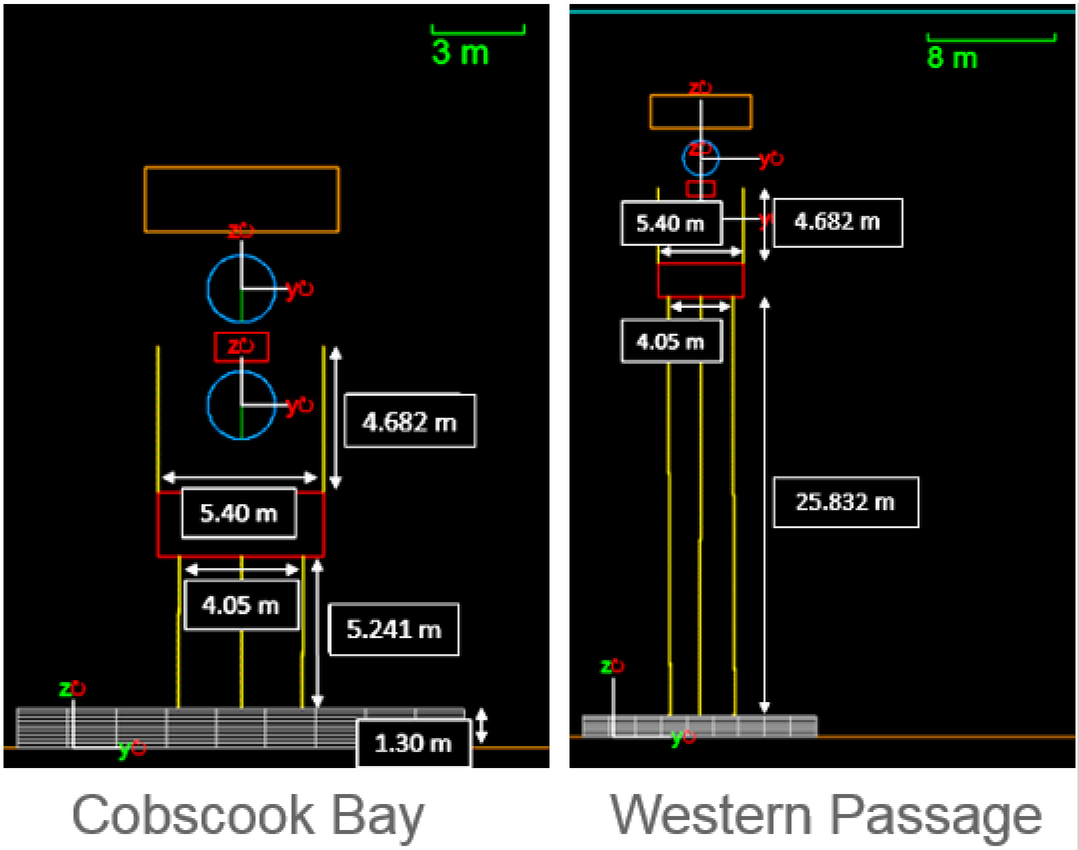


Figure 45. Mooring system arrangement for Cobscook Bay and Western Passage

Simulations for all load cases were performed for both the Cobscook Bay deployment and the Western Passage deployment site. The respective mooring arrangements are shown in Figure 14. Note that Cobscook is significantly shallower than Western Passage and this the mooring lines are quite short. During accidently limit cases (one of the mooring lines failing) this led to a higher shock load on the system even in a less energetic site. The driving load case for mooring lines is the accidental limit state where one of the bridle lines fails while the turbine is operating at peak flow, this leads to oversized mooring lines in design. ORPC investigated mooring line suppressors as a means to reduce the shock load to the lines and the chassis of the TidGen 2.0. One company TFI Marine completed an analysis where a section of each bridle line is replaced by a 3 meter long polymer and steel composite spring and were able to reduce the shock load on the system by 2230kN, this reduction is shown in Figure 15. The estimated cost of $25k per spring – plus an additional $100k NRE cost if ORPC cannot use an existing TFI Marine mold – makes the use of a spring attractive. By reducing the loads, the chassis will not require significant stiffening and smaller mooring lines can be used reducing capital cost, the amount of required buoyancy as well as easing on-shore handling of heavy chain and shackles.

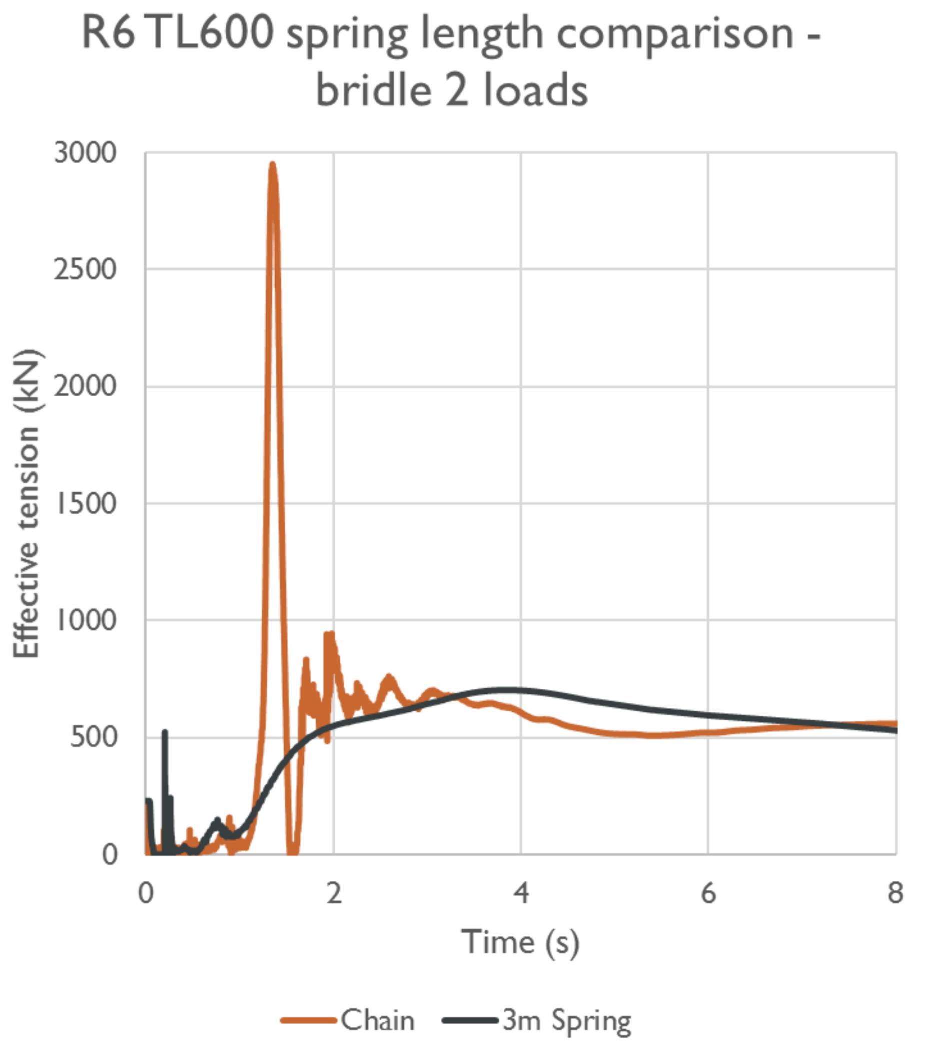


Figure 46. Shock load reduction with TFI Marine spring installed

The final analysis did reveal a concern about having redundant lines under low to no tension. As can be seen in Figure 16 the fore redundant line is likely to collide with the primary line which introduces the possibility of tangling and premature wear increasing the likelihood of line failure in both the redundant line and primary line. The aft redundant line may also touchdown on the anchor which is another significant concern. Most mooring line corrosion and wear occurs when a line touches down on the surface. Should the redundant lines wear early then if the primary line does snap they will not perform adequately to protect the device. Three options are identified to reduce these risks. The first is to increase the separation distance between the lines, this will prevent clashing of lines. The second is add additional abrasion protection to the lines. The third option is to add additional spreader bars between the lines tying them together and keeping them a fixed distance apart. A combination of all three solutions while reduce or eliminate the risk of line failure from clashing.

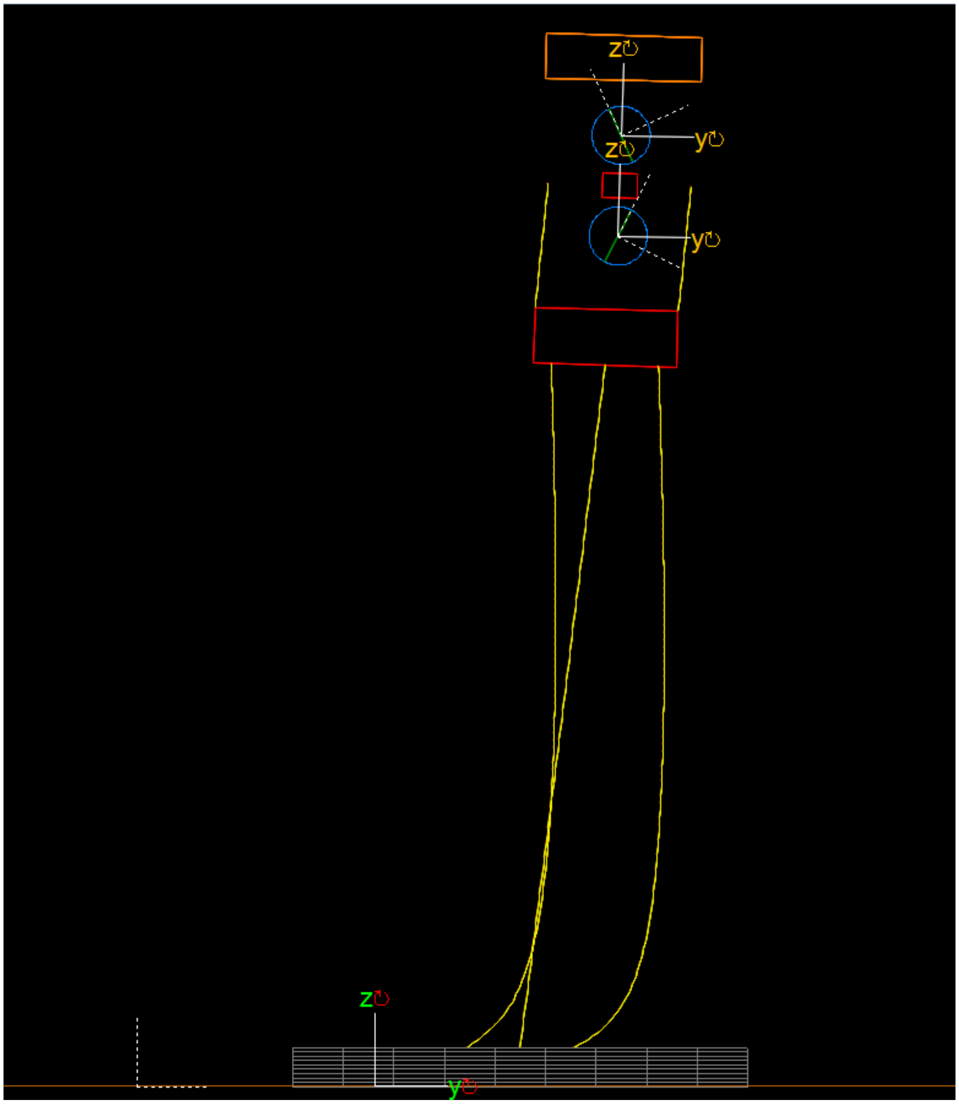


Figure 47. Redundant mooring line clashing

ORPC is also investigating alternative anchoring methods to gravity anchors. While providing the ability to deploy and retrieve the system and anchors in one tide cycles the size of the gravity anchors substantially increase the on-land and on-water operations costs. Alternative anchoring methods, such as micropiles, would require leaving the anchors in place when the device is retrieved and thus a connector is needed in the mooring lines. Most subsea mooring connectors are designed around having an ROV performing some of the operations. Typical ROVs are not suitable for the high current flows seen in tidal environments however an ORPC ARPA-E project developing pitching foils to be used as a propulsor and generator have revealed an opportunity to have an ORPC designed ROV utilizing crossflow turbines that operates very well in high flow environments. The suitability of alternate anchors will be investigated through budget period 2 during site investigates and anchor holding tests in Western Passage.

Task 4 Control System and SCADA

The following excerpts from Deliverable, D4.2 Control and SCADA System Design, which provides further design detail.

SCADA and Control System Description

The SCADA and control system of the Advanced TidGen® is separated into three areas of responsibility:

1. Control of turbine speed to maintain optimum efficiency, remain within allowable torque limits and remain below the limit of the power electronics. The "Control System" refers to this area of responsibility.
2. Supervisory control of the system including turning the system on and off, switching control system states and preparing the system for deployment and retrieval. The "SCADA system" refers to this area of responsibility.
3. Monitoring the performance and health of the system, alerting the SCADA system to any faults and logging sensor and status information for historical review. The "Condition Monitoring System" or CMS refers to this area of responsibility.

The control system operates on hardware independent of the SCADA and CMS and can manage any faults specific to the operation and health of the generator. The Advanced TidGen® operates two independent control systems, one for each row of turbines.

The SCADA and CMS operate on the same hardware. Unlike previous ORPC systems, the hardware is located on the device and can operate the device independently from the on-shore station. This allows for a controlled shutdown of the device in the event of a loss of communication or power from the shore station and continued monitoring of system health.

- **Communications Architecture**

The Advanced TidGen® will utilize a local ethernet network on the system to communicate between various enclosures, data acquisition modules and to network to the shore station. The controllers for each generator communicate over CAN-A bus and thus operate on a separate network. CAN-A is still relatively new to industrial automation and few industrial PLCs or DAQ systems can utilize the CAN bus, thus the backbone of the communication system was selected to be ethernet based.

- **Control Theory**

The control theory selected for this project was the $K\omega^2$ – a nonlinear feedforward controller. An analysis of alternative control theories is presented in ***D-TD20-10028 R00 – Preliminary Control System and SCADA Design DOE Advanced TidGen D4.1.***

Previous projects focused on control approaches evaluated four types of controllers which were tested in simulation, emulation, a laboratory flume, and the field[1]. Trends in simulation were verified through experiments, which also provided the opportunity to test assumptions about turbine responsiveness and control resilience to varying scales of turbulence. The clear message was that the feedforward $K\omega^2$

[1] EE0006397_ORPC_FINAL_TECHNICAL_REPORT

controller out-performs feedback controllers in almost all aspects and modes of evaluation. The controllers proved a substantial improvement over the baseline performance of the TidGen® turbine, in terms of energy capture.

- **Theory**

Derived from the dynamic model of turbine operation, the nonlinear feedforward Kω^2 controller commands a torque,

$$\tau_c = K\omega^2 = \frac{1}{2}\rho AR^3 \frac{\eta(\lambda)}{\lambda^3}\omega^2$$

which brings the turbine to a desired operating point on its performance curve ($\eta(\lambda)$). In the case where K results in the turbine operating at peak efficiency, this optimal gain is referred to in this report as K^*. K values larger or smaller in magnitude than K^* result in operation to the "left" or "right" of the peak (slower or faster than optimal λ, respectively). Optimal performance requires a well-defined performance curve and accurate measurement of ω. Note that unlike a feedback controller, the control torque equation does not explicitly prescribe a fixed set-point. Rather it controls the turbine to a set-point based on the estimate for the plant dynamics. This controller is shown schematically in Figure 1.

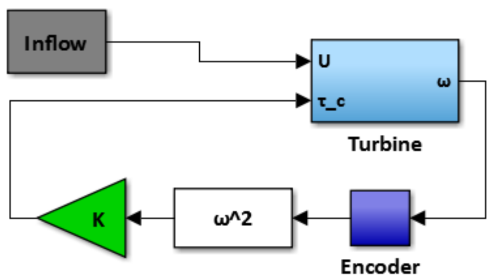


Figure 48. Kω2 controller schematic. This feedforward controller creates a torque command based on the speed of the turbine and the plant characteristic K.

- **SCADA Design**

The SCADA system is the link between the control system and the on-shore operation. The system can run in manual, semi-automatic and automatic mode.

In manual mode, the operator has complete control of the system, capable of switching states without automatically handling faults reported by the CMS. Important status readings will be displayed to the operator, however if the readings are outside normal operating conditions, the system will not take corrective action. Manual mode is intended for use during commissioning to more readily establish baseline readings and determine the operational conditions, as well as stress testing the system.
Semi-automatic mode is like manual in that the operator controls the switching of system states, however unlike manual control, the SCADA system will automatically handle any faults presented by the CMS. This may include a gentle or emergency shutdown of the system or change of control system commands to maintain integrity of the system. When an operator is present for maintenance, installation or removal the system is in semi-manual control.
Automatic mode is where the system is most likely to spend time. The SCADA system handles complete control of state switching; performing start-up and spin up of the turbines when the flow speeds reach useable levels, changing control mode between Kω^2, torque limited operation, power limited operation,

and shutdown as necessary. Any faults reported by the CMS will automatically be handled. In common faults, such as motor overspeed due to higher than expected current speeds, the SCADA system will automatically restart the Advanced TidGen® at the next tide cycle. Other faults such as bearing over temperature or water ingress in sealed compartments will alert operators and keep the system shutdown until operators can intervene. This last feature is required by DNVGL, any fault the triggers a shutdown will prevent a restart until the fault is cleared and an operator has restarted the system.

- **Condition Monitoring**

The condition monitoring system serves two purposes. The first is to provide a constant assessment of the health of the Advanced TidGen® while in operation. The second is to monitor performance and environmental information unnecessary to the operation of the Advanced TidGen® but useful for improving the design and functionality in the future. An instrumentation and equipment list can be found in Appendix C. The instrumentation and equipment are assigned unique identifiers according to ISA 5.1 Standards.

- **Warning and Fault Limits**

Sensors critical to the health and operation of the Advanced TidGen® are given warning and fault limits, used as indicators to the operator of abnormal behavior. Warnings are used as indication that a part of the system is entering an uncommon operational state. Warnings do not indicate a failure is occurring or imminent on their own, only to raise awareness and begin careful attention to all other systems. Faults are conditional limits that, when exceed the SCADA system must respond immediately, such as a shutdown of the system if a leak is detected in a compartment.

Most warning and fault limits cannot be determined before initial deployment. During the commissioning phase, the Advanced TidGen® will be operated at lower power outputs, with faults set low to both ensure the SCADA system is handling faults and to gain experience in what the steady state operational conditions are. In this phase, the SCADA system is typically left in a manual or semi-automatic mode and has constant operator attention making note of system parameters. Once defined, the system can be left in automatic control safely.

- **Data Logging and Backup**

A critical component to the CMS is logging and backup of sensors and control system parameters. The system must handle many inputs with varying levels of importance and sampling frequencies and keep a record of them backed up in multiple locations in the event of a failure anywhere along the network line.

Depending on the current and previous state of the system, the data logging procedure is different. Those procedures and conditions are as follows:

- **Rolling Log**: A continuous log of the last hour of system status and intersystem communications is kept. This log is continually overwritten, stored locally and not logged unless some condition requires it.
- **Power Production Operation**: When the system is operating normally and actively producing power, system health and status information is logged at most every minute. Voltage and current are monitored at each generator, converter, and before and after the transmission line. Leak sensors are not logged.

- **Shutdown Operation**: When the system is shutdown, such as between tide cycles, system position and environmental conditions are logged. Power systems and leaks systems are not logged.
- **On Fault**: When a fault in the system is detected, the rolling log is immediately backed up locally and to the shore station. The system then enters a high data rate logging of all power production and rolling log parameters until the system has successfully shutdown.
- **On Shore Connection Loss**: When the Advanced TidGen® loses connection to the shore station, the On Fault logging begins. Once complete standard Rolling Log and Shutdown Operation logs are suspended and a low power, low rate log is initiated. Only critical system parameters are recorded. This is to preserve adequate storage space for logs on the device, until re-connection or recovery is performed and to minimize the power draw of the system, ensuring the longest period of operational time while connection to the shore is lost.

The logs are kept in three separate locations. The first is locally on the device, where at least the last 24 hours of operations is kept. These logs are automatically backed-up by the shore-station every 6 hours. Depending on the shore-station storage capacity, months to years of historical data is kept. Each day, the logs are backed-up to an offsite location accessible by ORPC for monitoring and review.
It is important to differentiate between monitoring and logging. All sensors on the Advanced TidGen® are actively monitored by the CMS. Monitored sensors are sampled at the program clock frequency, typically faster than 10Hz. This information is also displayed to the operator at the shore station in real time. Logged data is kept for historical review and must be stored. Sensors such as leak detection, enclosure pressure and temperature, oil pressure and humidity do not change frequently and do not provide any useful information historically, therefore are not logged, but actively monitored.

- **Development Path and Subsystem Testing**

The development of the control system is largely independent of the Advanced TidGen® design and development path. The remaining development of the SCADA and Control system is:

1. Identification of any outstanding sensors not yet defined.
2. Internal layout of electronics enclosures and associated wiring diagrams
3. Subsea cable specification
4. Software development of the PLC code
5. Interface testing with vendor equipment such as the converter and brake
6. User Interface development for the PLC code

The last phase of the development takes place after final assembly of the system and before installation. A system integration test will checkout all sensors are reading properly and that the generators and brakes operate successfully.

ORPC is currently developing the next generation RivGen®, schedule for deployment a year before the first installation of the Advanced TidGen®. In the interest of keeping components and design common between products, the RivGen® will utilize the same SCADA and control system architecture as the Advanced TidGen® despite being a significantly smaller device. As a part of the development and testing of the SCADA and control system, ORPC will install the system on the RivGen® and perform software development and testing early. The core software and user interface will be able to be copied directly to the TidGen® system. Doubling as a test system, the RivGen® does not use the same converter electronics and generator as the TidGen®, however the driveline, enclosures and environmental monitoring are all sufficiently similar that determination of warning and fault limits for the TidGen® can start with that of the RivGen®. In all, the development of the RivGen® SCADA and control system will significantly reduce the development time and risk of the Advanced TidGen®.