CalWave
Power Technologies

CWPT Open Water Demonstration
DE-EE0008097.0000
Budget Period 1

Final System Design with System Integration Plan

May 2019

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VARIABLES & DEFINITION

FURTHER CONVENTIONS

CalWave is using the following convention for the positioning and orientation of the global coordinate system. This convention is equal to the most common convention used in Naval Architecture and specifically in wave energy conversion related research & development:

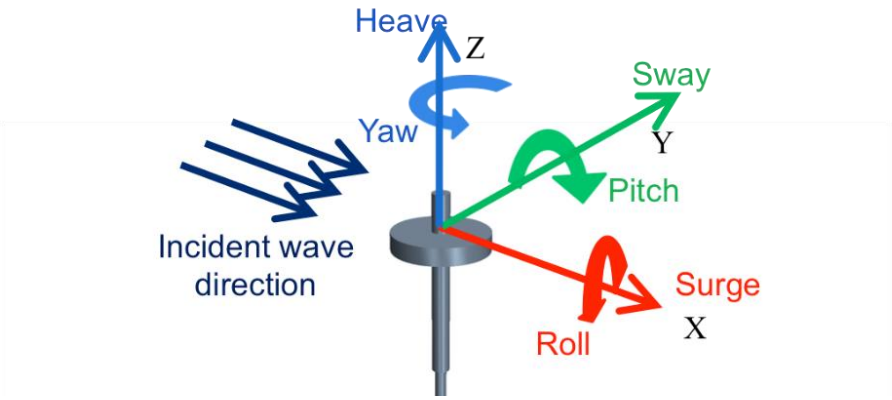


Figure 1: Global Coordinate System Position and Orientation used throughout this report. Picture / Scheme by WECSim - Theory section (https://wec-sim.github.io/WEC-Sim/theory.html)

ABBREVIATIONS

MBL – Minimum Breaking Load (Mooring Line Property)
PTO – Power Take-Off
WEP – Wave Energy Prize
MPC – Model Predictive Control
COG – Center of Gravity
COB – Center of Buoyancy
MOI – Moment of Inertia
AM – Added Hydrodynamic Mass
AD – Added Hydrodynamic Damping
DOF – Degrees of Freedom
MLLW – Mean Lower Low Water (Measure of Ocean Surface)

1. INTRODUCTION

This report was generated during Budged Period 1 of the DOE-EERE 'Marine and Hydrokinetic Technology Development and Advancement' grant with project number DE-EE0008097.0000. The objective of this project is to advance the Technology Readiness Level of the Wave Energy Converter (WEC) developed by CalWave Power Technologies Inc (CalWave) through advanced numerical simulations, dynamic hardware tests, and ultimately a scaled open water demonstration deployment while continuing to exceed DOE's target ACE threshold of 3 meters/M$. The outcomes of Budget Period 1 will be a detailed design of the scaled demonstration unit and bench testing of the critical hardware components. In Budget Period 2, the key outcomes will be deployment and operation of the demonstration unit at an open water site which replicates full scale ocean conditions, and performance and load measurements will be used to validate the high techno-economic performance of the full-scale device, as measured by the "Average Climate Capture Width per Characteristic Capital Expenditures" (ACE) metric defined for the Wave Energy Prize.

This report describes the final systems design and system integration plan and is a comprehensive review of the CalWave demonstration WEC's functionalities, operations, design requirements and considerations that lead to the selection of the listed subsystems and components.

2. CALWAVE DEVICE DEMONSTRATION

CalWave's WEC design addresses the fundamental challenge in wave energy conversion: the large differential between wave energy flux during typical conditions and rare but powerful storm conditions and extreme events which contribute little to annual energy production but dramatically increase structural costs and thus hinder cost competitive electricity production. Conventionally, the conversion steps from ocean waves to device oscillations, to the power take-off dynamics, and ultimately to the electrical grid has been approached as a series of discrete steps, each with their own challenges and solutions. This approach grafts itself well into traditional engineering domains and leverages established modeling techniques, design tools, and industrial processes. However, this segmented approach risks optimizing individual links in the power conversion chain, while creating new challenges and inefficiencies at the interface between the constituent parts.

In contracts, CalWave's approach is considering the entire chain of conversion steps as a single process with intrinsically connected requirements and optimization potential for performance and cost-efficient device design via synergies. In this view, the limits of one step in the power conversion chain are critical to effectively control the next. Co-optimized WEC hulls, PTOs, and electrical export frameworks must be considering holistically, acknowledging the dynamic characteristics of their adjacent components, to efficiently work together.

This holistic design approach unlocks a vast potential for performance improvement via a holistic control approach: the ocean wave load input into the primary wave-structure energy capture step is no longer considered to be constant based on a single absorber design but is included into the holistic device control framework itself. This unique approach maximizes energy flux, achieving consistent and high utilization of the device's capacity over a large range of wave states, while efficiently protecting the device from extreme waves.

Following a structured systems engineering approach, CalWave has developed a submerged pressure differential type WEC which is based on a holistically controllable system approach. A single body submerged oscillating device is positively buoyant and taut moored to the sea floor and combines multiple unique features distinguishing it from other device designs.

In this project, a scaled version of CalWave's WEC design will be deployed in open water to demonstrate its energy capture performance and ability to actively manage the wave loads acting on the device. The demonstration WEC is a single horizontally oriented absorber body with the main function of handling the fluid-structure interaction for high performance wave to mechanical energy conversion. The absorber body reacts against the seabed through taut mooring connected to anchors. The mooring lines are connected to the main structure through PTO winches that allow adjustments to the active line lengths which in turn can change the operating depth of the device. The device operates in the upper water column, submerged below the free water surface. More details about absorber hull are in **Section 4A**.

The loads on the WEC hull are converted into electricity by the Power Take-Off (PTO). This drivetrain includes mechanical, hydraulic, and electrical components which work together to smooth the irregular wave inputs into a clean, steady electrical power output. The demonstration WEC's drivetrain is discussed in detail in **Section 4B**.

The mooring solution for the demonstration deployment is discussed in **Section 4C**.

An array of other subsystems is required to safely and effectively maintain a WEC in a harsh offshore environment. **Section 4D** describes the Supervisory Control and Data Acquisition (SCADA) system onboard the WEC, which is responsible for collected signals from inside and outside the WEC, processing the data and generating commands, and relaying all this data to CalWave's engineers. **Section 4E** provides an overview of the electrical power connection between the WEC and an onshore monitoring station, and **Section 4G** focuses on the umbilical cable that makes this connection. Finally, **Section 4F** collects information on the small but important auxiliary systems that keep the WEC safely operational at sea.

3. SYSTEM FUNCTIONS AND OPERATIONS

The following section describes system functions and operations that lead to the device specification used for the design and TRL advancement of the subsystems during BP1. The primary objective of the demonstration WEC is to absorber wave energy and efficiently convert it to electricity. However, special operational modes be planned ensure safe installation and maintenance, avoid storm loads, and manage potential subsystem faults.

IEC TS 62600-2, *"Marine energy – Wave, tidal and other water current converters – Part 2: Design requirements for marine energy systems"*, defines Design Load Cases (DLCs) or operational states meant to capture the system requirements in the various conditions it may encounter. Depicts these operational states, and the transitions between them, specifically for CalWave's WEC.

IEC DLC	Design Condition	Partial safety factor	Sea state type	Water Level	Wave Height [m]
1.1	Normal Operation	ULS, FLS, SLS	Normal stochastic sea state	NWLR	Hs,in < Hs < Hs,out
1.2	Normal Operation	ULS, FLS, SLS	Normal stochastic sea state	NWLR	Hs,in < Hs < Hs,out
1.3	Normal Operation	ULS, FLS, SLS	Normal stochastic sea state	NWLR	Hs,in < Hs < Hs,out
2.1	Normal operation with fault	ULS, FLS, SLS	Normal steady wave height	NWLR	Hs,rated < Hs < Hs,out
3.1	Start procedures	ULS, FLS, SLS	Normal steady wave height	NWLR	Hs,rated < Hs < Hs,out
4.1	Normal shut down procedures	ULS, FLS, SLS	Normal steady wave height	NWLR	Hs,rated < Hs < Hs,out
5.1	Emergency shut-down procedures	ULS, SLS	Normal steady wave height	NWLR	Hs,rated < Hs < Hs,out
6.1	Parked/survival conditions	ULS, FLS, SLS	Normal stochastic sea state	NWLR	Hs50
7.1	Parked plus occurrence of fault	ULS, SLS	Extreme stochastic sea state	EWLR	Hs1
8.2	Transport, installation and maintenance	ULS	Extreme stochastic sea state	NWLR	HS1

Table 1: IEC TS 62600-2 ED2 Design Load Cases

DLC 1: Wave energy absorption and conversion

The layout of the mooring and PTO allow energy extraction from all degrees of freedom of the fully submerged absorber. The absorber body oscillates around an equilibrium position in a controlled manner under the action of wave excitation to extract power from the waves. During normal operation, an exposed winch drum converts the linear displacement along the mooring belts to rotary motion of the four PTO drive shafts. The major part of the driveshaft is enclosed in the device's pressure hull with only the winch drum, ~30 cm of shaft sections on both side of the winch drum, and two low friction rotary seals in contact with the surrounding water. The rotary seals on the shaft on either side of the winch drum facilitate the shafts transition from the ocean environment to the sealed air volume inside of the device with biodegradable lubrication. Common absorber body's displacements during regular operation for surge, heave and pitch.

The velocity of the device oscillation cannot exceed the velocity of the fluid particles of the wave acting on the device. Thus, typical durations of oscillations around the average displacement values provided above are in the range of 3 – 10 seconds.

Other DLCs: Device operations: Installation, maintenance, shut-down and decommissioning

There will be times when the WEC cannot safely or effectively operating in energy absorption mode and must transition to another operating mode. During installation, maintenance, or recovery (DLCs 8.1, 8.2, & 8.3), the device is at the surface and requires interaction with human operators and vessels. At other times, though the device is in perfect working order, ocean conditions may be unfavorable and requirement a "idle" mode, in which the WEC focuses on avoiding excessive wave loads rather than power production (DLC 6). Faults among the WEC systems can also occur; depending on the severity and risk, power production may continue (DLC 2), or may not (DLC 7).

4. SYSTEMS AND SUBSYSTEMS DESIGN DESCRIPTION AND INTEGRATION

In the following section, the first and second level subsystem and components are listed and described.

Table 2: System and Subsystem Identification.

ID		Component
A.0000		Hull
	A.0100	Pressure vessel - housing all dry equipment
	A.0200	Entrapped Water Hull
	A.0300	Hull Access Hatches
B.0000		PTO
	B.0100	Mooring Line Connection
	B.0200	Fairlead
	B.0300	Mooring Winch
	B.0400	Clutch & Brake
	B.0500	Motor/Generator
	B.0600	Gas Spring
	B.0700	Power electronics
	B.0800	Capacitor Bank
C.0000		Mooring & Anchoring
	C.0100	Line Connection
	C.0200	Mooring Line
	C.0300	Anchor
D.0000		SCADA
	D.0100	Hull Measurements
	D.0200	PTO Measurements - Electrical/Mechanical
	D.0300	PTO Measurements - Hydraulic
	D.0400	Communications
E.0000		Electrical Plant
	E.0100	Battery Energy Storage
	E.0200	WEC-Side Switchgear
	E.0300	Shore-Side Switchgear
F.0000		Auxiliary Systems
	F.0200	Bilge
	F.0300	Hydraulic System
	F.0400	Climate control
	F.0500	Data logging
G.0000		Umbilical
	G.0100	Export Cable
	G.0200	Connectors
	G.0300	Cable Seakeeping and Anchoring

A-HULL SUBCOMPONENTS

The device consists of one wave actuated body that sits completely submerged in the water column. The shape of the absorber is approximated as a rectangular prism or cuboid, where the length (x-direction) and width (y-direction) are of equal size, while the thickness (z-direction) is smaller than the other characteristic dimensions. The center of the absorber body is completely open and only covered by the load management hatches.

A.0100 Pressure Vessel

The CalWave demonstration WEC hull will be constructed of welded steel covered with a common ship antifouling coating, compliant with the International Anti-Fouling System (IAFS. Physical properties of the hull are listed in Table 3 with principle dimensions indicated in the drawing in Figure 2. The hull outer shell is reinforced with internal flat bar steel stiffeners, as shown in Figure 3. The hull structure is almost entirely welded together and serves as the supporting structure for nearly all other WEC components.

Table 3: Physical Properties of the Hull.

Physical Characteristic	Measurement
Length	4.3 m
Width	4.3 m
Height	1.6 m
Cuboid Volume	19.7 m^3
Mass	~8,800 kgs
Average depth of ocean at deployment site	21 m
Above water profile	0 m
Material(s)	steel
Surface coating(s)	antifouling paint

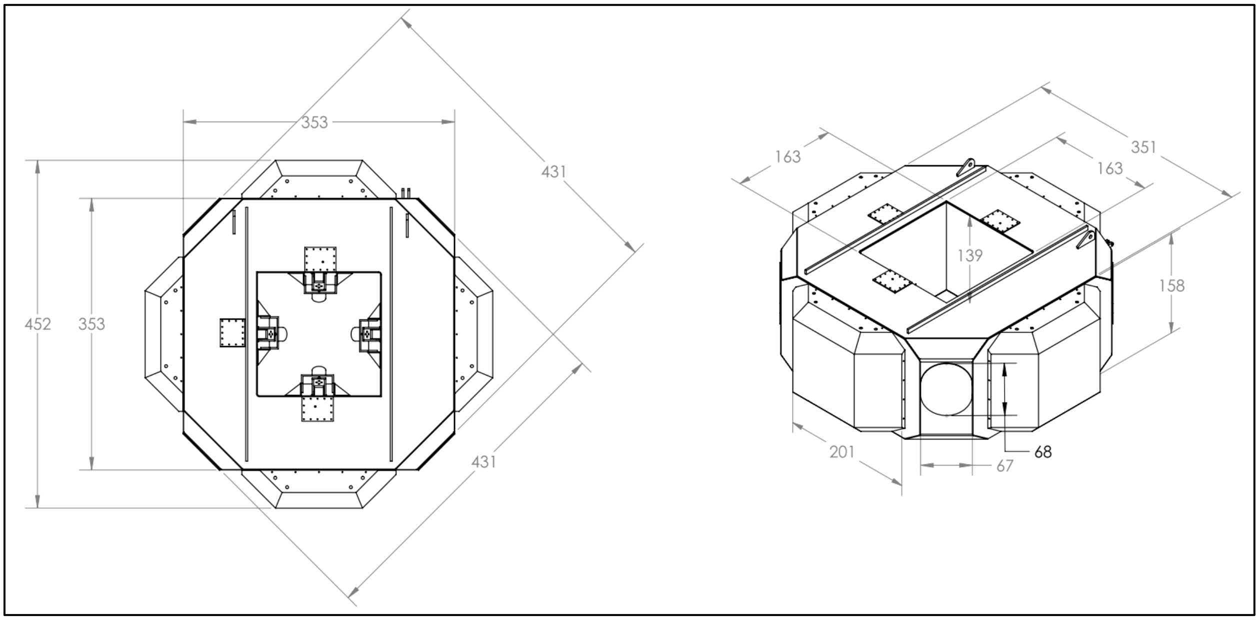


Figure 2: Hull layout general (dimensions in cm).

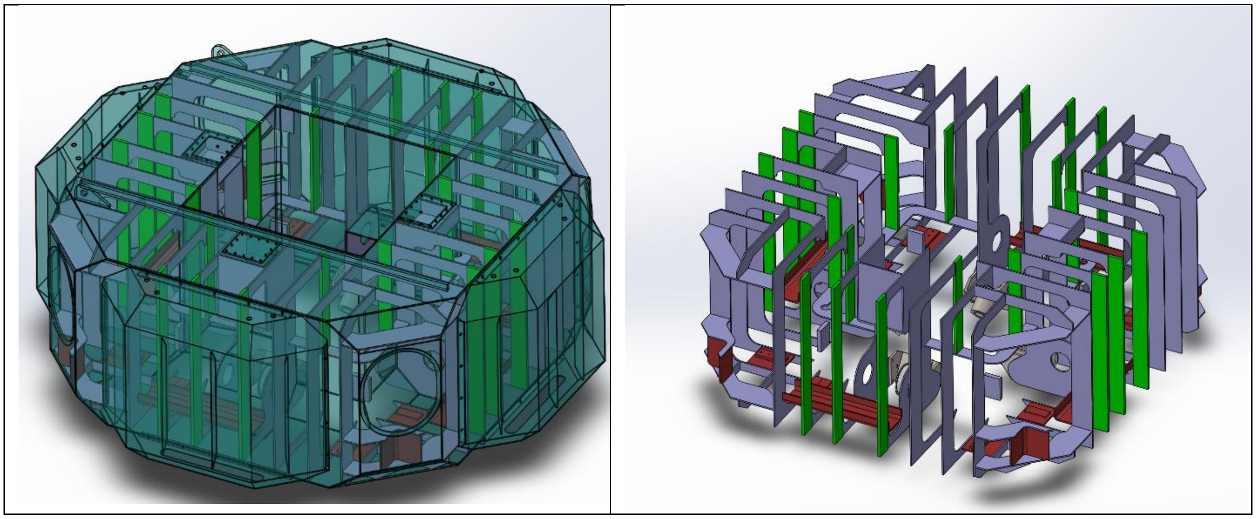


Figure 3: Hull shell and stiffener general layout.

A.0200 Entrapped Water Hull

The water entrapment pods are separate structures that attach to the hull, each weighing 240 kgs. The entrapment pods are fixed to the hull with mounting bolts on four sides attaching to threaded plates welded to the hull. The entrapment pods are in yellow in Figure 4, with one pod removed to show the mounting plates.

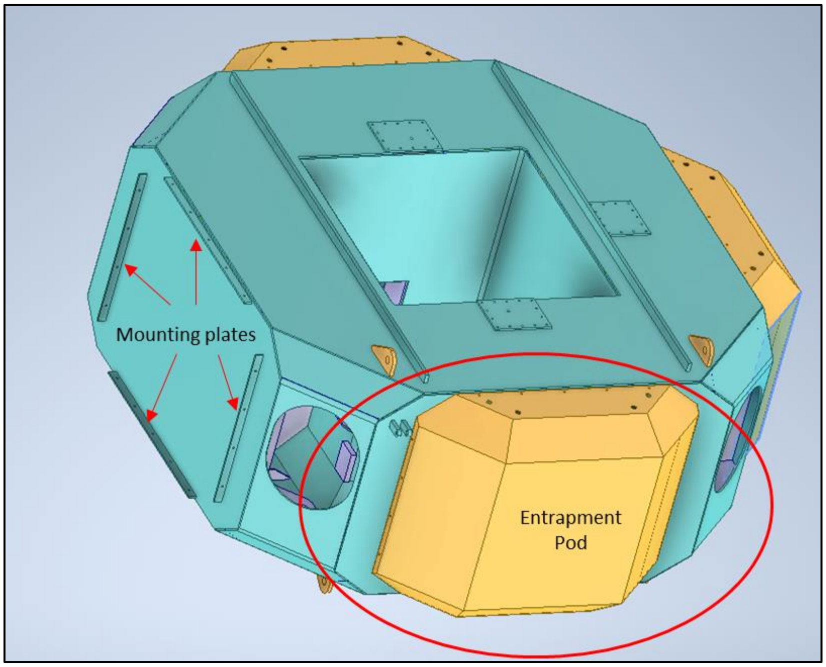


Figure 4: Water Entrapment Chamber.

A.0300 Hull Access Hatches

All internal WEC components, including electrical, hydraulic, and mechanical elements of the PTO assemblies, will be installed through access hatches on the side of the absorber hull. Two of the four access hatches are shown with annotated dimensions in Figure 5.

The largest assemblies to be installed through the access hatch are the shaft spring (245 kg, 430 mm diameter, 1300 mm length) and the motor/gearbox assembly (328 kg, 420 mm diameter, 800 mm length). The access dimensions are such that these assemblies can fit with 170-180 mm horizontal clearance and give enough vertical clearance for lifting rigging.

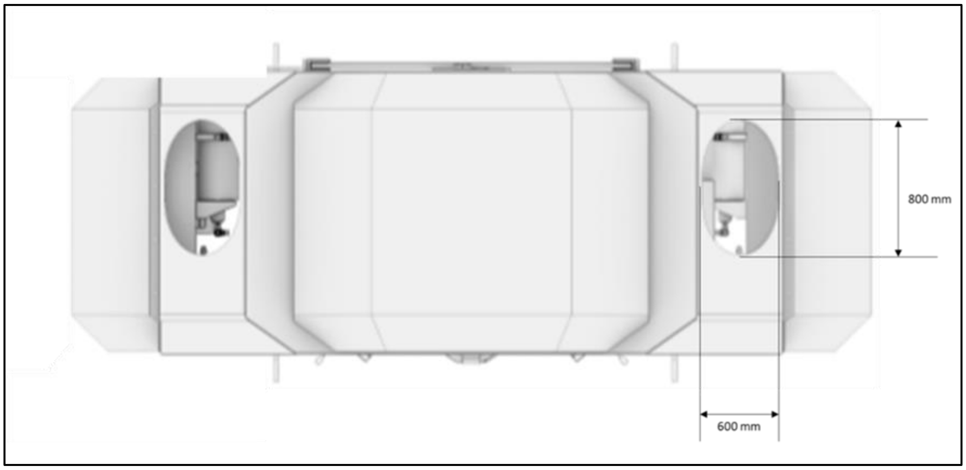
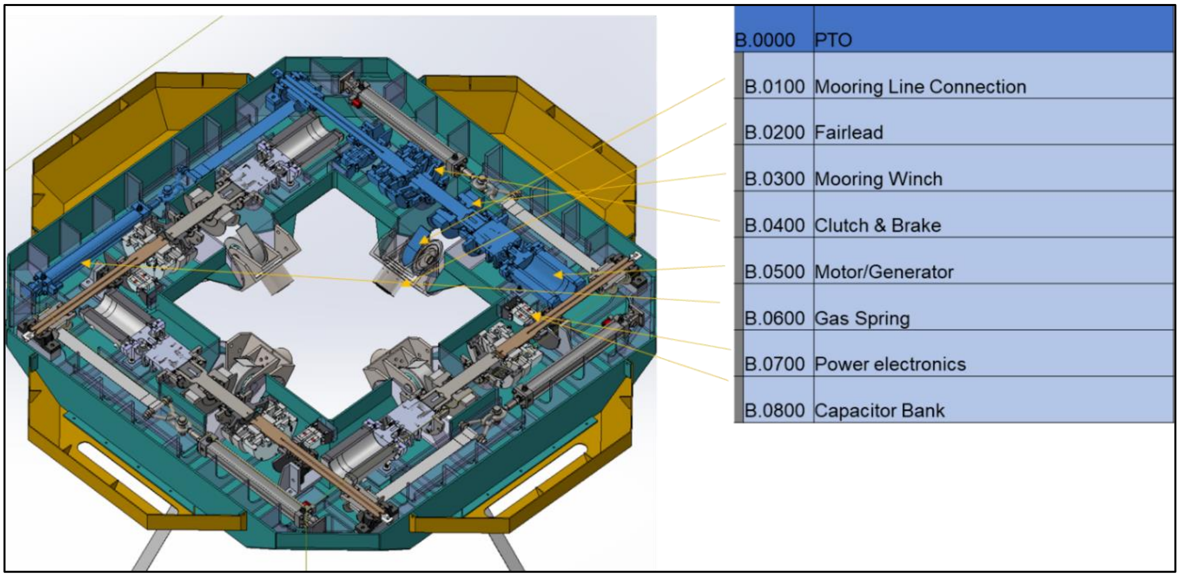


Figure 5: Access Hatch Dimensions.

B- POWER-TAKE OFF SYSTEM SUBCOMPONENTS

The WEC includes four identical PTO systems, the components of which are shown in Figure 6. For clarity, an individual PTO is shown in Figure 7. At the center of the device, a fairlead directs the mooring belt to the mooring winch drum upon which it wraps up, shown in Figure 6. The mooring winch includes a horizontal shaft that connects all the PTO components with a discontinuity at the clutch. The clutch allows for the winch drum to displace independently of the gas spring; the brake holds the gas spring in place while the clutch is disengaged. The motor/generator puts power into and removes power from PTO and interfaces through a gearbox. The gas spring applies the required pretension to the PTO and mooring line to offset the device buoyancy, thus avoiding a static torque offset requirement from the motor and avoiding associated copper losses. Power electronics integrate with and control the motor/generator while a capacitor bank allows for short term electrical energy storage.



B.0000	PTO
B.0100	Mooring Line Connection
B.0200	Fairlead
B.0300	Mooring Winch
B.0400	Clutch & Brake
B.0500	Motor/Generator
B.0600	Gas Spring
B.0700	Power electronics
B.0800	Capacitor Bank

Figure 6: CAD drawing of wave excited body with four PTO units; with the main components of the PTO drive train labeled.

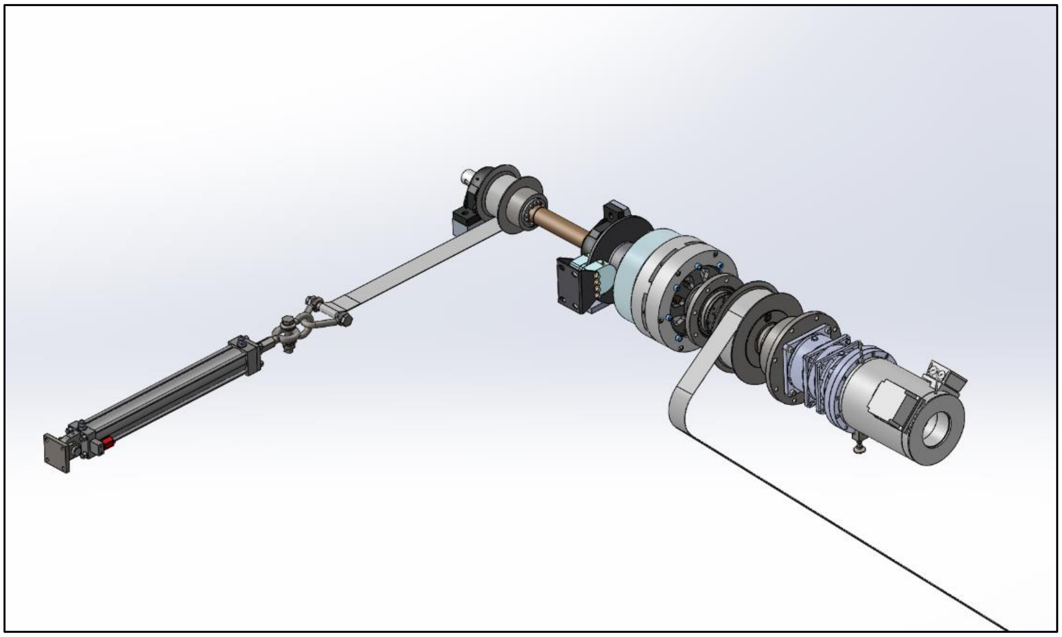
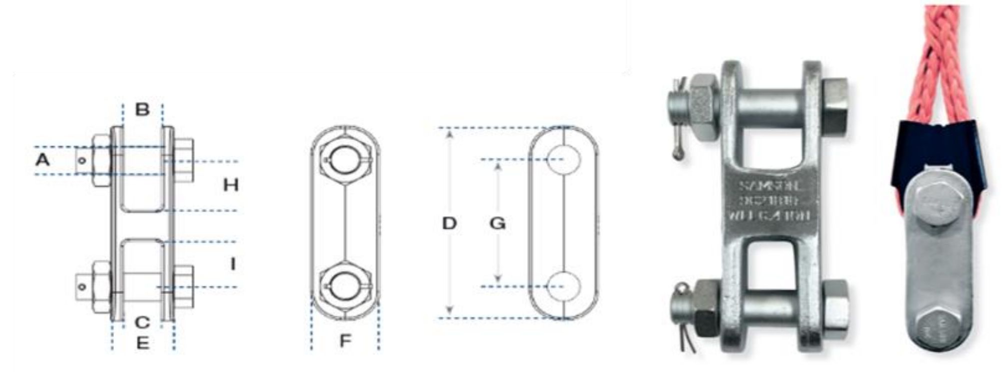


Figure 7: CAD drawing of individual PTO

B.0100 Mooring Line Connection

An HMPE webbing belt supplied by TTS Innova interfaces between the mooring drum and mooring line. A belt form factor was chosen over a rope to improve the cyclic bend over sheave (CBOS) fatigue life. A webbing sling shackle is used to connect to the mooring line whereas a pin connects the belt to the winch drum. The gas spring belt is similarly connected to the gas spring drum and gas spring hydraulic cylinder.

Due to the width of the PTO Belt, a custom H-link sling shackle is required for this connection, improving fatigue resistance and reducing risk of belt edges rubbing on connection hardware. Figure 8 shows a representative example of a similarly sized product.



Working Load Limit	Pin	Top Gap Width	Bottom Gap Width	Overall Length	Width	Depth	Pin Separation	Top Gap Height	Bottom Gap Height
WLL	A	B	C	D	E	F	G	H	I
8.4 tons	1.38"	1.7"	1.7"	9.5"	2.8"	3.1"	6.2"	2.2"	2.4"
	35 mm	42 mm	42 mm	241 mm	70 mm	79 mm	157 mm	56 mm	61 mm

Figure 8: Standard H-link Adaptor.

This basic product design concept will be maintained and modified to allow for the difference between the width of the flat belt and mooring line. The below Figure 9 illustrates dimensions and concept modifications for the required fabricated design.

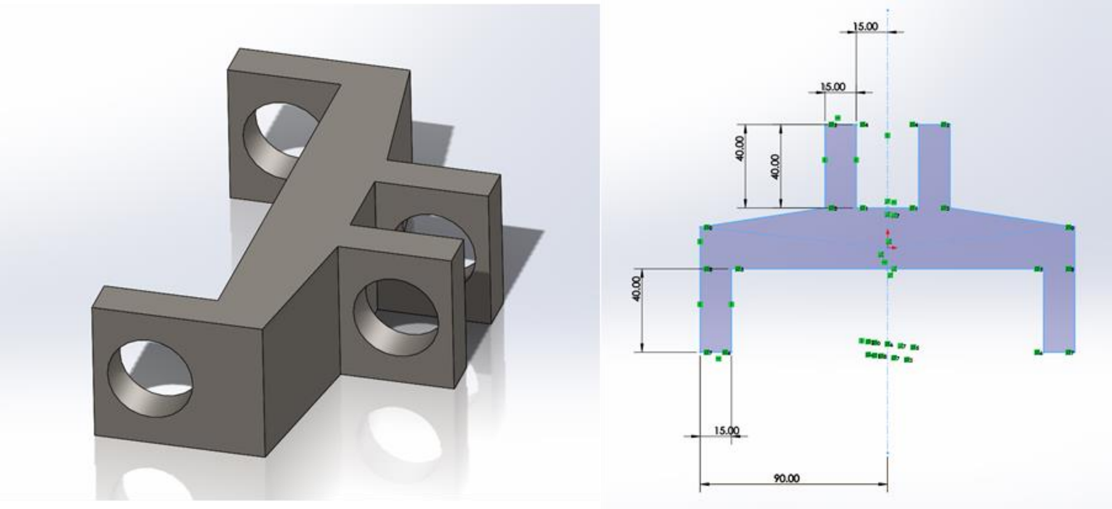


Figure 9: Modified H-link Adapter Design.

The pin for the mooring line side of the H-link adapter can be a standard marine 1” shackle bolt, with nut and cotter pin for added security. During deployment it will be noted not to tack weld the nut in place, which is often a tempting method of ensuring against inadvertent loosening but has negative effects on load characteristics particularly in terms of fatigue loading. For the belt side H-link adapter pin the non-standard length will require a special order.

B.0200 Fairlead

The fairlead, shown in Figure 10, allows for the belt to turn in two degrees of rotation. The primary degree of freedom consists of a pully that is capable of a full 360° of rotation while the secondary degree of freedom allows the pully to rotate up to 30° out of plane. The construction utilizes DuraBlue composite bushings and 316 stainless steel structural components. The bushings are sea water lubricated, can adequately withstand both the expected radial and thrust loads, and can achieve a coefficient of friction between 0.1-0.2 when running against the 316 steel shafts.

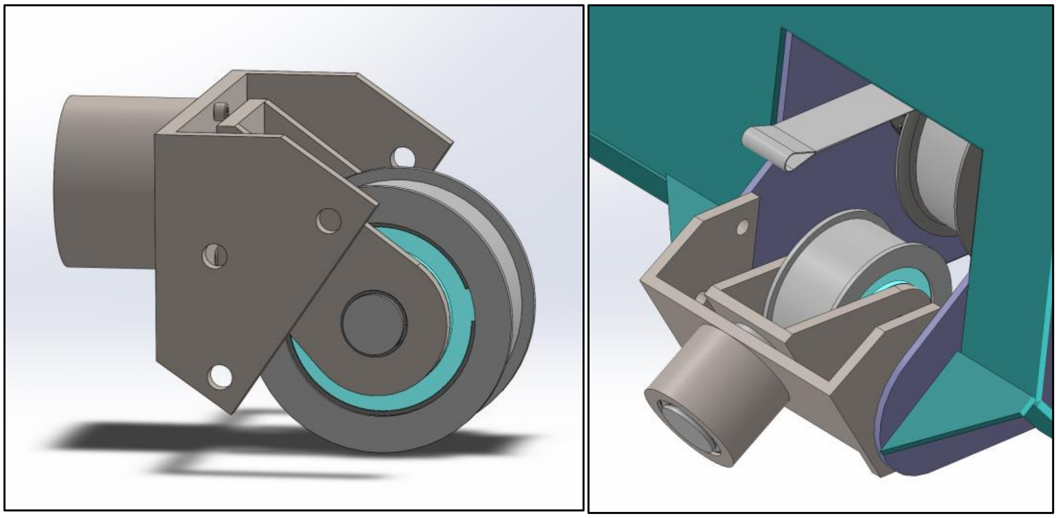


Figure 10: CAD of fairlead subcomponent (left) with close-up of hull integration (right).

B.0300 Mooring Winch

The mooring winch wraps and unwraps the mooring belt for a linear to rotary mechanical power conversion. It interfaces to the other PTO components through its shafts, as shown in Figure 11.

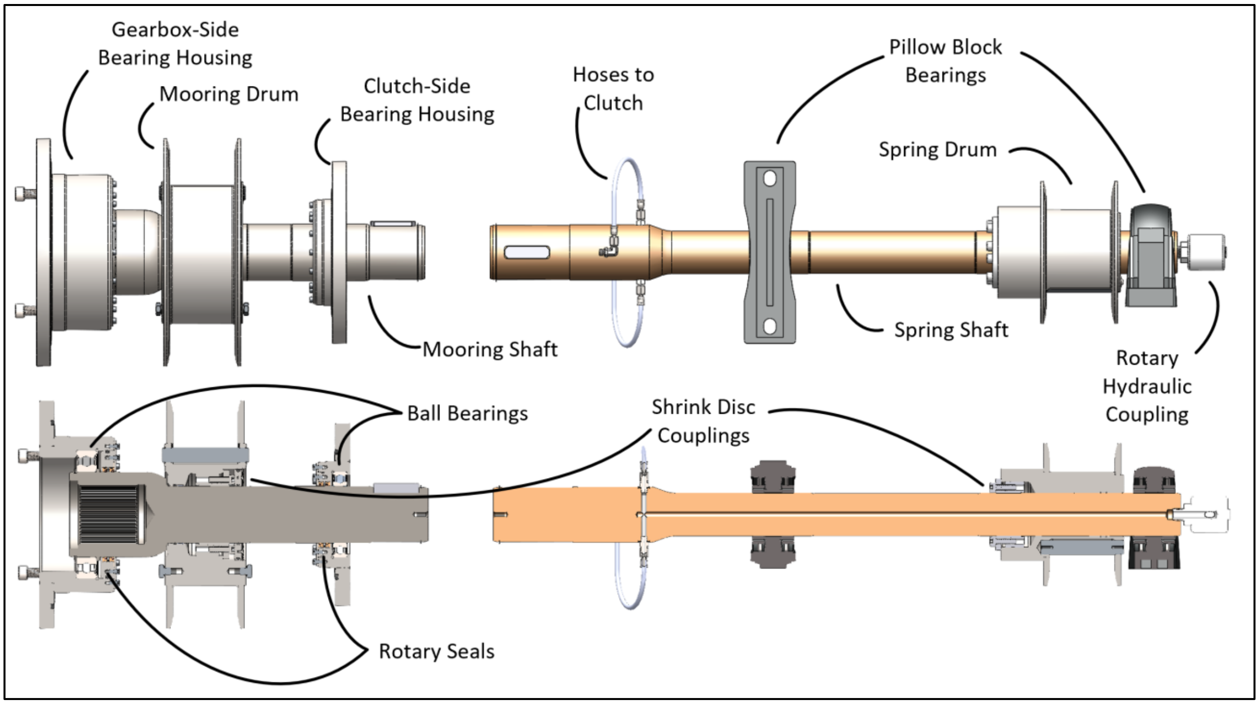


Figure 11: CAD rendering and cross section view of the mooring winch.

Structural components

The winch drum shaft is machined from P750 stainless steel. Originally developed for oil field applications, this grade of stainless steel has especially high pitting and corrosion resistance. These properties are important as this shaft is partially exposed to seawater and provides the sealing surface for the dynamic seals. The shaft is also passivated for improved corrosion resistance.

The spring drum shaft is machined from AISI 4340 HRC high strength alloy steel and nickel plated for improved corrosion resistance. A high strength alloy was selected to keep the shaft compact. The shaft includes a partially hollow center to allow hydraulic fluid to be pumped through a rotary coupling on the shaft end to the clutch.

All other structural components, including the winch drum, spring drum, clutch side bearing housing, and gearbox side bearing housing, are machined from AISI 316 stainless steel and passivated for corrosion resistance. The winch and spring drums are secured to their respective shafts with Ringfeder wedge type shrink disc couplings. A sealing cover is placed over the winch drum coupling to prevent exposure and corrosion.

Seals

A set of dynamic rotary seals prevent the ingress of water at the hull penetration locations of the mooring drum shaft. Seals were provided by Eclipse Engineering, drawings of which can be found in Figure 12 for the gearbox side interface. These seals are spring energized, allowing any built-up air pressure inside the hull to be released while preventing seawater ingress. Two seals are used at each shaft interface for redundancy, with an additional hydrophobic grease pack in between.

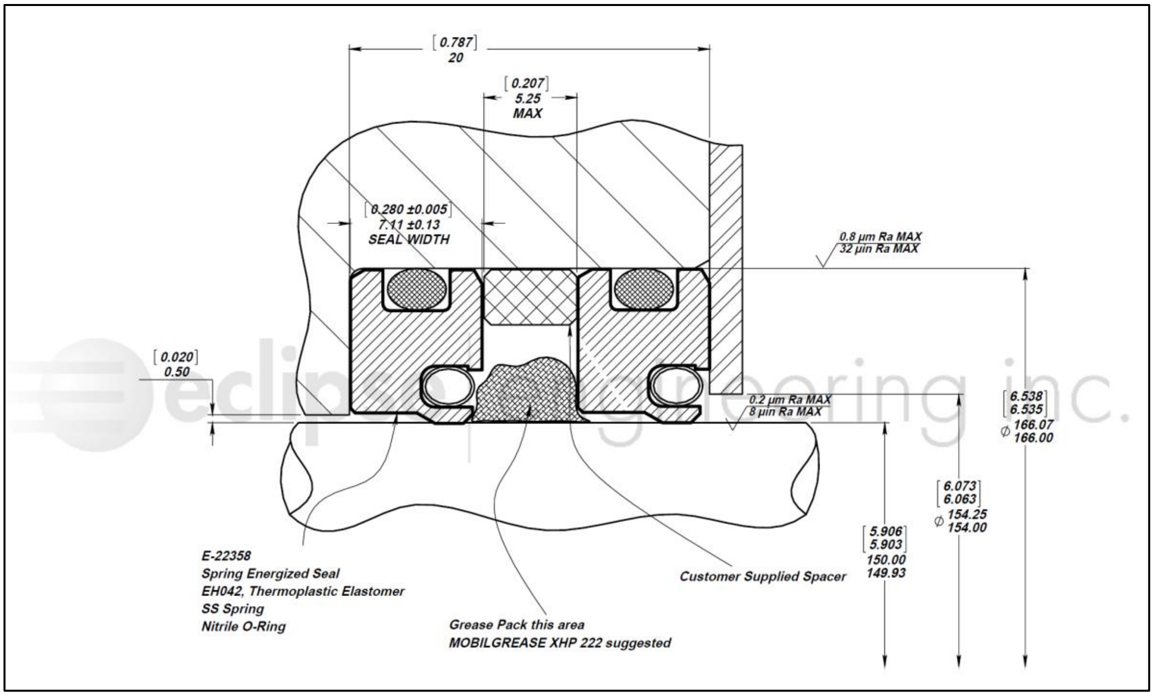


Figure 12: Cross sectional drawing of the dynamic rotary seal design on the gearbox side of the mooring drum shaft. Drawing provided by Eclipse Engineering Inc.

All static seals in the PTO structure are off the shelf O-rings made from Viton and allow for simplified manufacture of components.

Bearings

The mooring drum shaft is supported by two SKF deep groove ball bearings. The gearbox-side bearing is rated for a dynamic load of 120 kN while the clutch-side is rated for a dynamic load of 63.7 kN. The spring drum shaft is supported by two SKF roller pillow block bearings, each rated for a dynamic load of 212 N. These bearings sufficiently meet the required dynamic load capacity.

B.0400 Clutch & Brake

Clutch

The clutch allows the spring shaft and mooring shaft to spin independently of each other. This is necessary in depth change operations to decouple the fixed gas spring stroke from the less limited mooring line stroke. A custom friction clutch was designed by Wichita Clutch, a subsidiary of Altra Industrial Motion. A cross sectional drawing and CAD images provided by Wichita Clutch are shown in Figure 13. The clutch is spring set, hydraulically fully released at 103 bar (1500 psi), and specified to transmit up to 5330 Nm of torque. A custom clutch was necessary because the required torque is above the range of common off the shelf components.

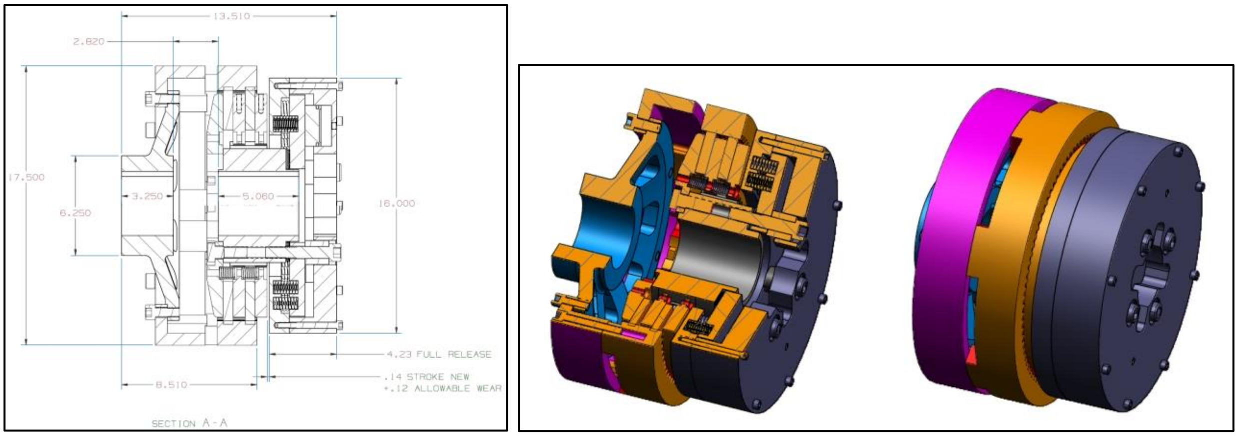


Figure 13: Clutch cutaway drawing (left) and CAD Isometric views (right). Note all dimensions are in inches. Provided by Wichita Clutch (Altra Industrial Motion).

A key slot and interference fit transmits the torque between the two sides of the clutch and their respective shafts. and Because the clutch driven end (purple) and clutch end (orange/grey) are installed separately, the clutch is used as the reference point to measure alignment between the spring and mooring drive shafts. Dial indicators are used to measure the angular and parallel misalignment between the two shafts which can then be corrected by shimming the supports.

Brake

The brake holds the spring shaft and gas spring in place when the clutch is disengaged. A hydraulic caliper disc brake from WC Branham was selected and can provide up to 3600 Nm of static holding torque under 103 bar (1500 psi) of hydraulic pressure. The brake is also capable of suppling 3600 Nm of braking torque dynamically, although this feature is not expected to be used except in emergency situations requiring immediate shaft deceleration. Various drawing views of the brake can be found in Figure 14. The brake disc is machined from 4140 AISI HRC alloy tool steel to be 38 cm in diameter and 1.27 cm thick. The brake disc is secured to the spring drum shaft with a Ringfeder wedge type shrink disc couplings.

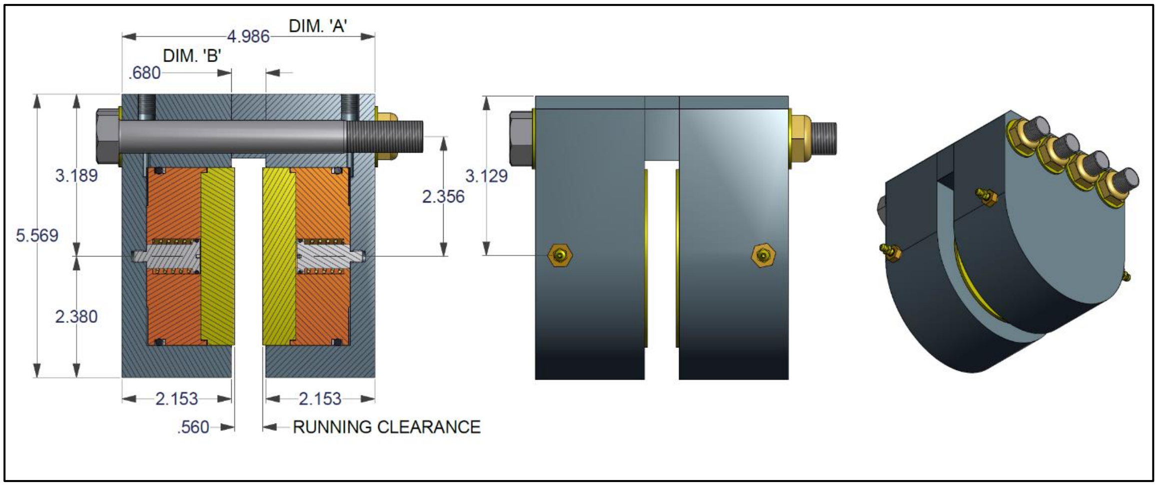


Figure 14: Drawing views including cutaway (left), top (middle), and isometric (right) of the caliper brake. Note all dimensions are in inches. Supplied by WC Branham.

B.0500 Motor/Generator

The electric motor/generator is from Siemens' 1FW3 line of permanent magnet synchronous machines (PMSM), which are specifically designed for high torques and low speeds in a compact form factor. A torque-speed curve of our machine (1FW3155-1DH72-5AA0) is below in Figure 15; the high torque availability at near-zero RPM is a crucial characteristic for our oscillating system, which passes through zero speed with every wave cycle. The machine itself, installed on the drive train, is shown in Figure 16.

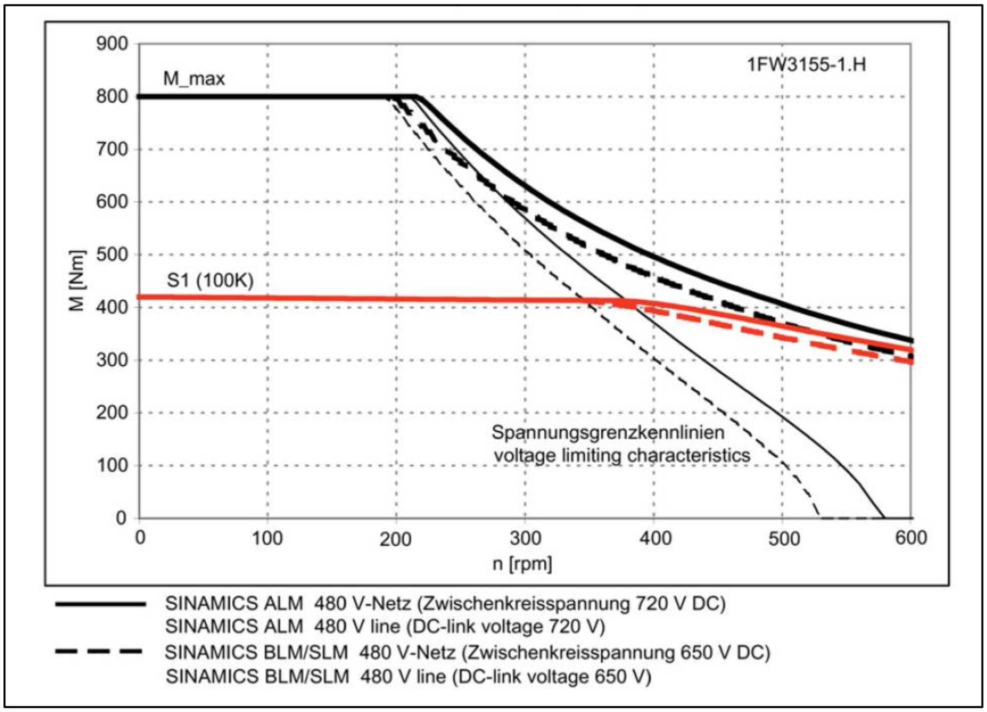


Figure 15: Speed/torque characteristic of the PMSM motor/generator.

Figure 16: Siemens 1FW3 PMSM installed on the PTO test bench.

The electric motor actuates the drive shaft via a gearbox, specifically the Servotak SGH-5000 series; our gearbox is highlighted in the catalog page in Figure 17. This model was chosen for low backlash and thus minimizes "dead-band" areas of poor controllability near moments when the torque direction changes. The hollow-shaft Siemens 1FW3155 motor is physically connected to the Servotak SGH-5000 gearbox with a custom adapter plate; assembly drawings for the motor and gearbox are in Figure 18.

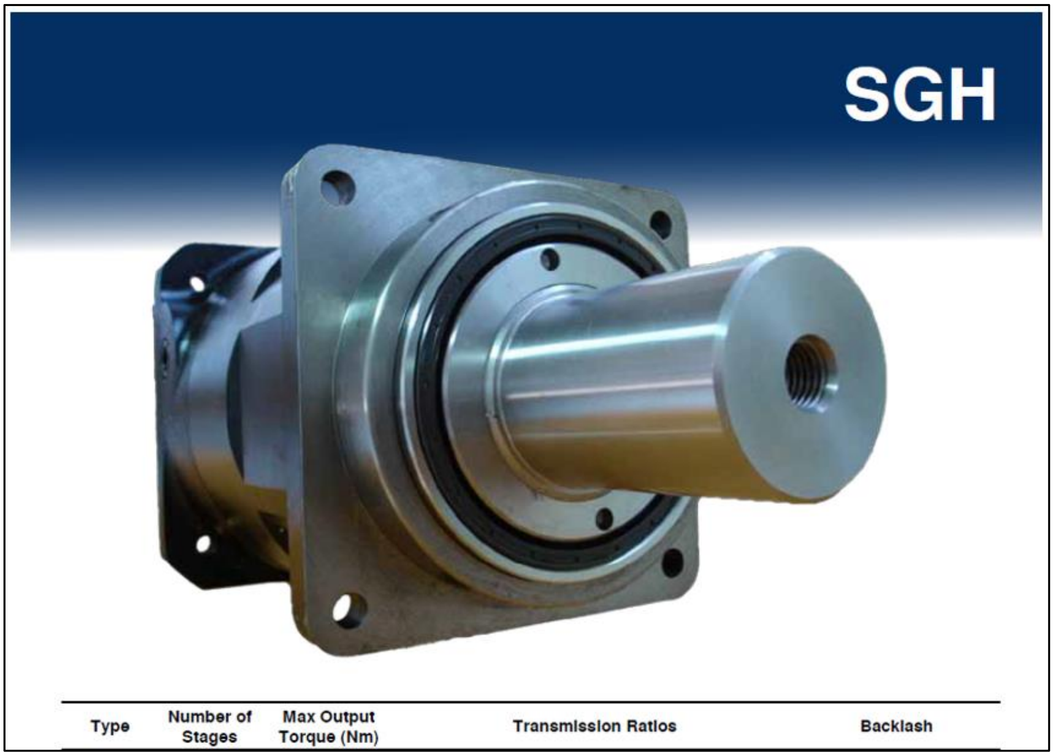
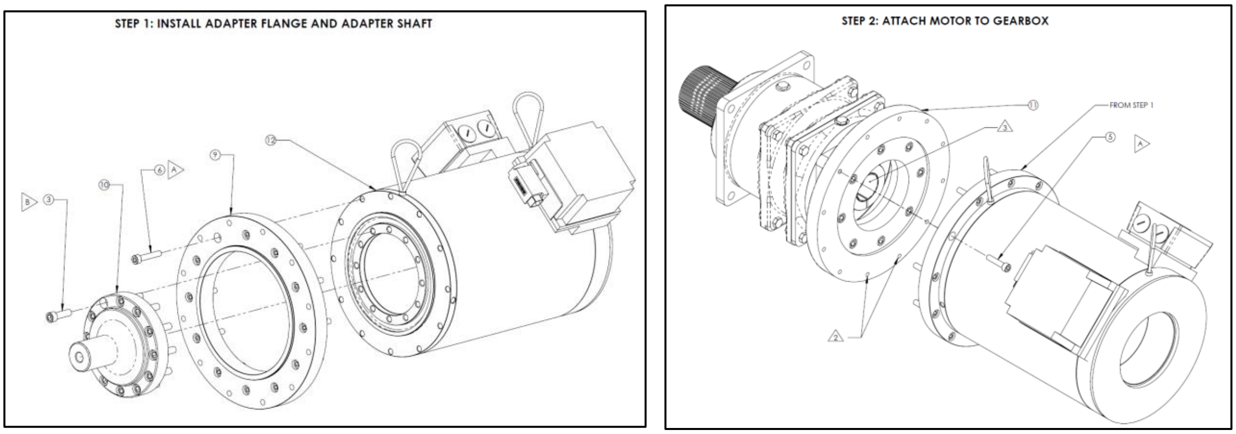


Figure 17: Servotak SGH-5000 Gearbox.



(a)

(b)

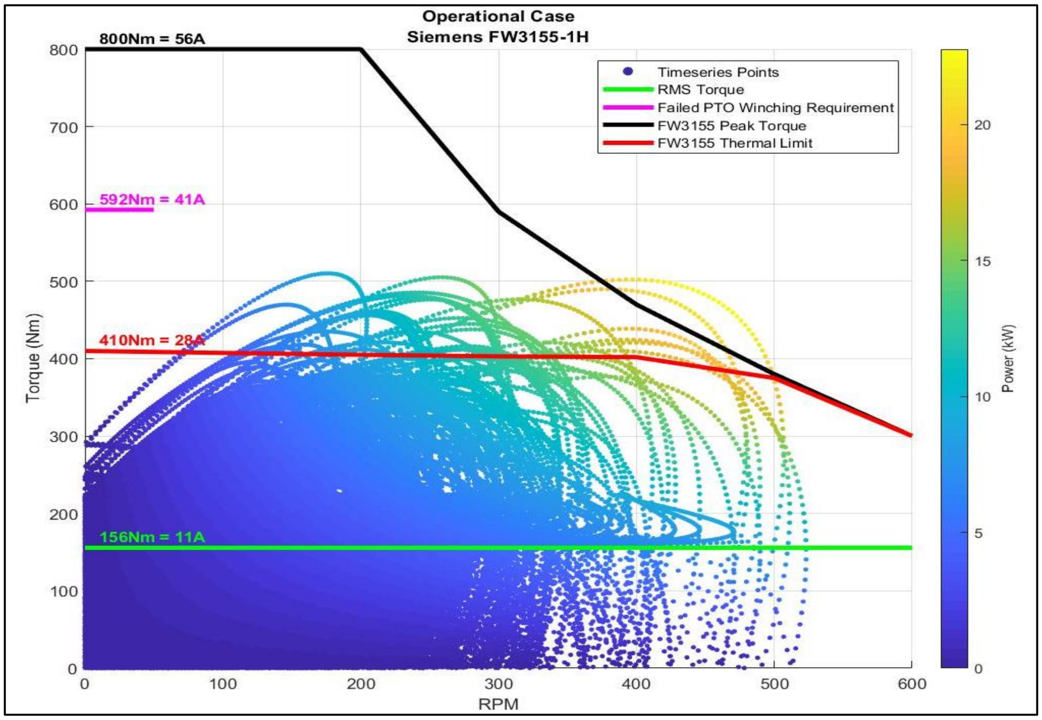
Figure 18: Motor and gearbox assembly. (a) Addition of custom shaft adapter; (b) Mounting of motor to gearbox.

The motor and gearbox were sized as a pair to accommodate 3 conditions:

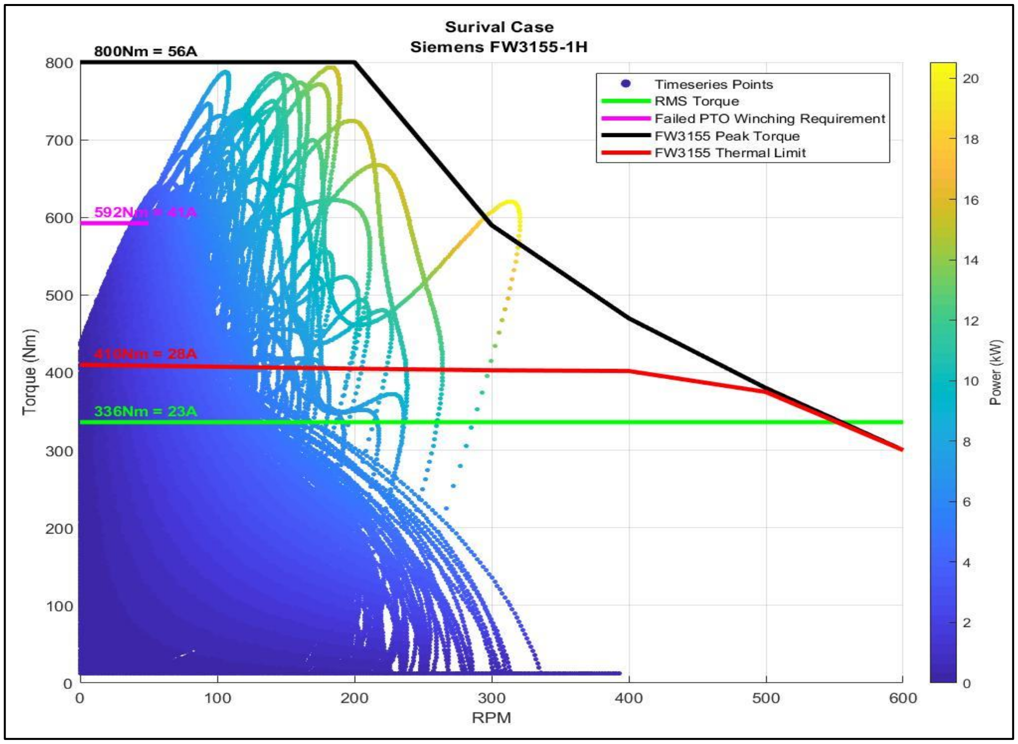
1. Normal Operations, in which the gas spring is acting on the drive shaft and the WEC is programmed to maximize energy capture.
2. Survival Mode, in which the gas spring is declutched the motor is responsible for PTO action to “de-tune” the WEC from large incoming waves.
3. Failed PTO Winching, in which only 3 of the 4 motors are responsible for pulling the device down to safety depth.

The first two conditions are represented in speed-torque scatter plots (derived from tank test experimental data) in Figure 19, while the third condition is represented on both plots by the small magenta line at 592 Nm. One key observation is that the expected speed-torque relationship is almost always below the black peak torque line, and excursions beyond the peak torque can be handled with a combination of more advanced controls and field-weakening in the electric machine.

Another useful observation is that the RMS torque on the motor (the green line), which is a product of current flow and thus a proxy for heat generation, is below the motor’s thermal limit (red line), suggesting that no active cooling is needed. The magenta line representing the “failed PTO winching requirement” is above the thermal limit, but this winching torque will only be present as the device is pulled to safety depth, and thus should avoid significant heat build-up.



(a)



(b)

Figure 19: Representative torque-speed relationships for the motor during normal operations (a, top) and survival conditions (b, bottom).

B.0600 Gas Spring

A schematic of the gas spring is shown in Figure 20 while an image of the hydraulic circuit is shown in Figure 21. It consists of a single hydraulic cylinder, an accumulator connected to the rod-side port, as well as valves (relief valve, bleed valve) and sensors (pressure, temperature). The cap-side port is connected to the reservoir in the supporting hydraulic components, causing the cap side of the cylinder to operate in steady low pressure.

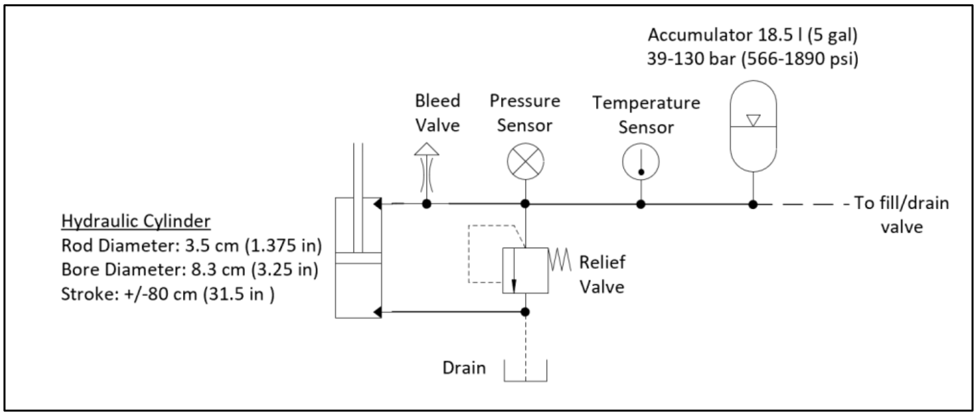


Figure 20: Schematic diagram of gas spring hydraulic circuit.

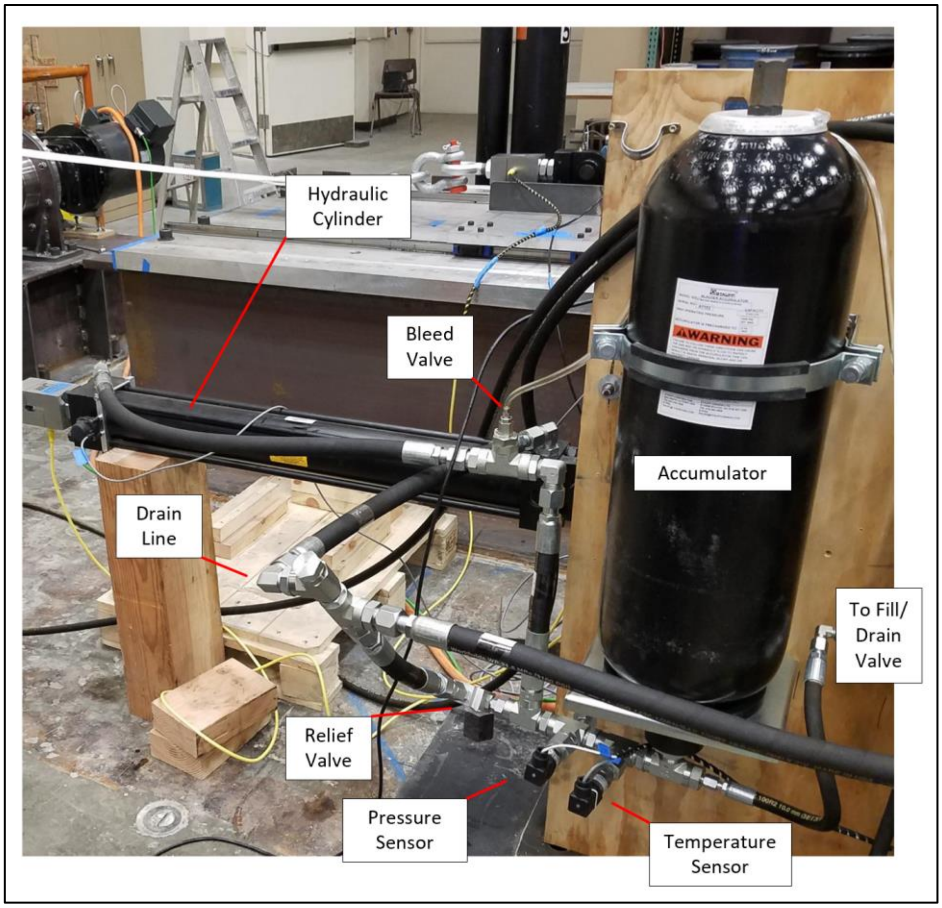


Figure 21: Picture of physical gas spring hydraulic circuit.

The gas charge in the accumulator is provided during commissioning and left unchanged throughout deployment. A directional valve allows additional hydraulic fluid to be added into the high-pressure line or let out. This allows the spring to adjust equilibrium position or pretension that can vary with device depth or system temperature. Specifications of the gas spring are given in expected performance curves of the gas spring are given in Figure 22. Note that the gas spring was modeled using the ideal gas law and assumes adiabatic operation of the nitrogen gas charge with a polytropic exponent of 1.5. Depending on how the WEC is operated, varying pretensions are needed in the gas spring. The design driving case occurs when the device is deepest submerged and restricted to operating only on 3 of the 4 PTOs. This case is referred to as the 3 PTO Survival case.

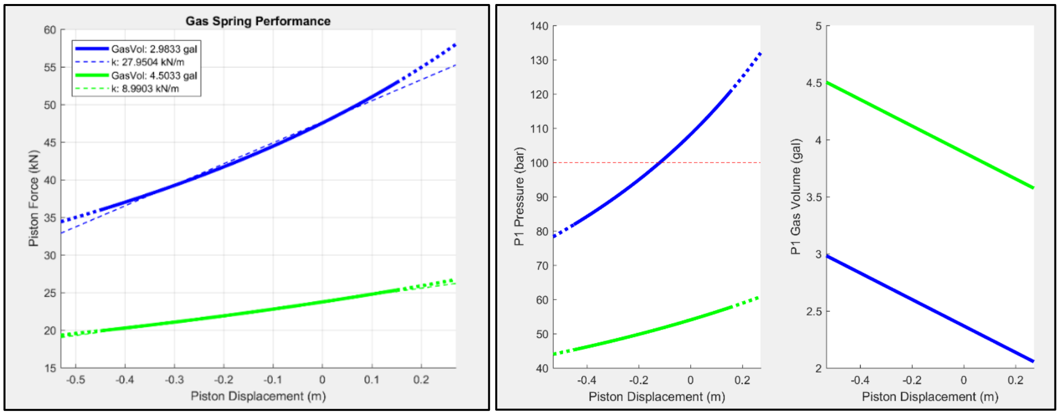


Figure 22: Analytical model results of gas spring characteristics during normal operation (green) and 3PTO survival case (blue).

B.0700 Power Electronics

The motor is controlled using Siemens' S120 line of variable frequency drive (VFD) components. The S120 system offers a modular approach to configure a "back-to-back" inverter topology for controlling many independent drive axes from a common AC electrical supply. A generic back-to-back VFD scheme is shown in Figure 23, illustrating the conversion of an AC supply to an energy storage on an internal DC bus, and ultimately again to AC excitation on the coils of the electric motor; our embodiment using S120 components is shown in the top half of Figure 34. For bench testing a single motor module is connected to the DC bus, but 3 additional motor modules can be easily added to control each PTO in the ocean-going WEC. The controls, configuration, and communications of the 4-motor arrangement can be adapted from the single-motor installation, so much of the development effort for safe operation of the motor on the test bench should be avoided when transitioning to the full WEC installation.

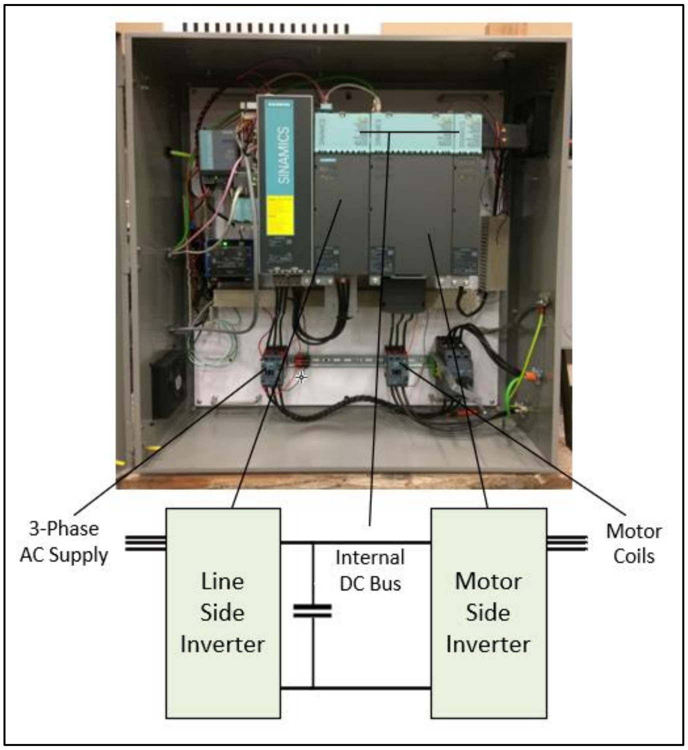
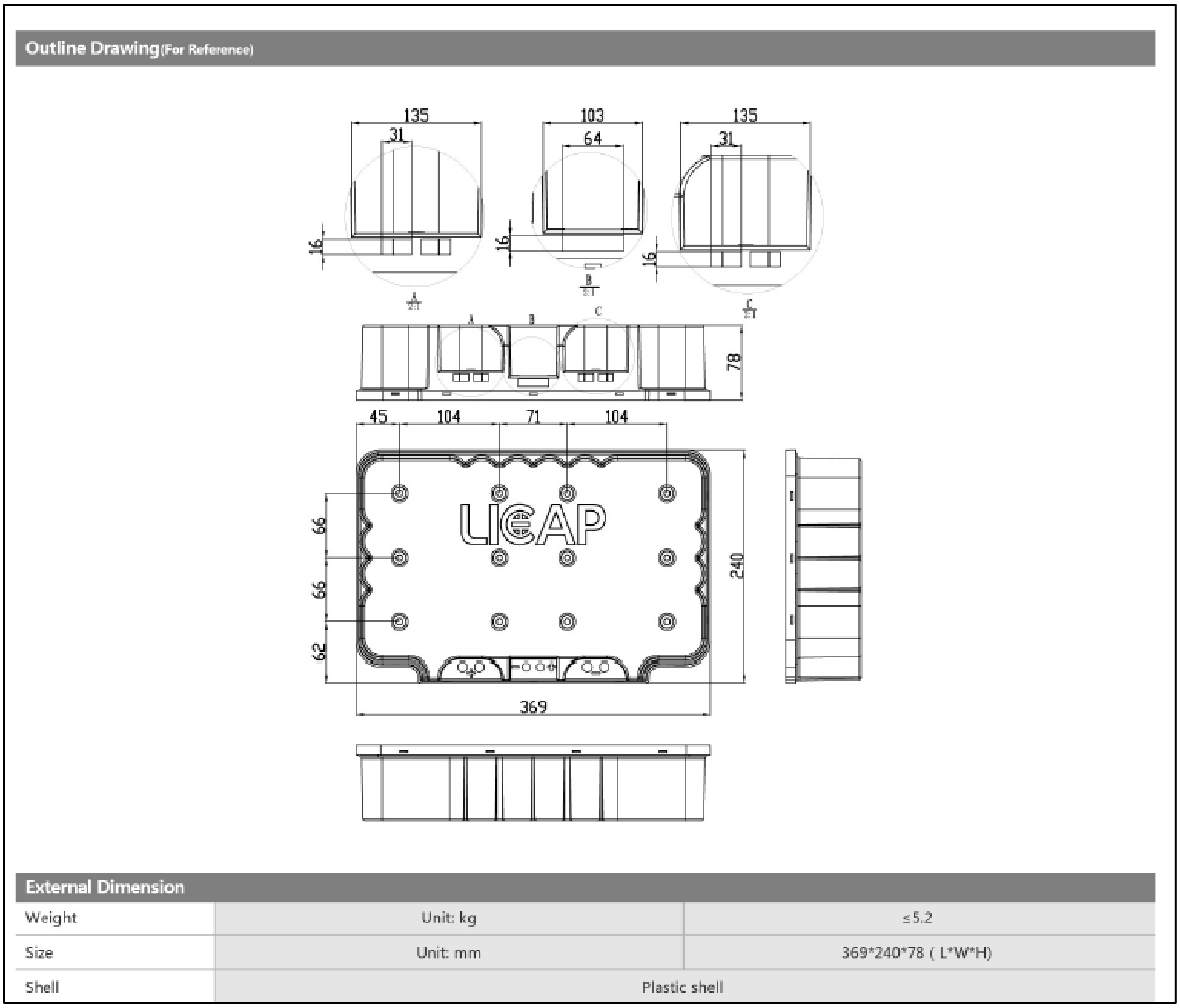


Figure 23: Siemens VFD lineup and corresponding generic back-to-back inverter topology.

B.0800 Capacitor Bank

Our application uses a variable frequency drive with regeneration functionality to control a permanent magnet synchronous machine in frequent transitions between motoring (net-negative energy) and generating (net-positive energy) modes. The long-term average is for net positive energy capture, but to maintain resonance with the waves, relatively large swings in power must be accommodated. Rather than taking these large currents to and from the export cable, we prefer to balance them on board using ultracapacitors, e.g. LICAP's 160V, 5.8F modules, shown in Figure 24. The bank of ultracapacitors is connected in parallel to the motor side inverter on the VFD's internal DC bus.



Outline Drawing(For Reference)

External Dimension

Weight	Unit: kg	≤5.2
Size	Unit: mm	369*240*78 (L*W*H)
Shell	Plastic shell	

Figure 24: LICAP Capacitor Module.

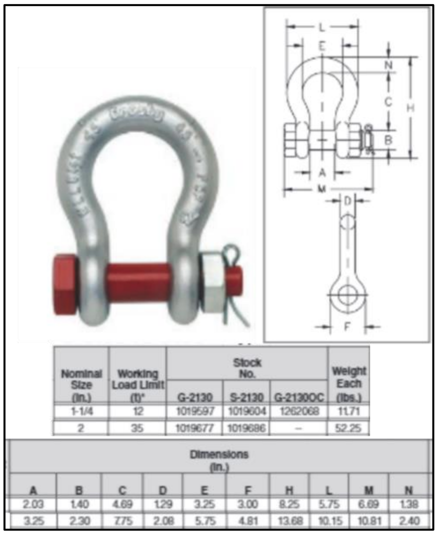
A schematic of our power electronics circuits is below. The DC link in the VFD will be broken out to an external bidirectional DC-DC buck-boost converter, which will interface the VFD's internal 650V DC bus with the external ultracapacitor bank. The topology works well in rudimentary simulations, and a representative time series output for two configurations is also below.

C-MOORING SUBCOMPONENTS

The mooring system encompasses all the components that keep the WEC on station and create a stable force reference for the PTOs. A flat belt serves at the interface between the PTO's winch drum and the mooring line which reaches to the anchors on the sea floor.

C.0100 Line Connection

Depending on the anchor selected, either a standard marine bow shackle or H-link bracket will connect the anchor to the HMPE mooring line. As this connection point will remain submerged for the duration of the deployment, considerations for corrosion and fatigue wear will be incorporated into the design safety factors. Given the differential between dry weight and apparent submerged weight and the typically larger safety factors involved in lifting hardware, the connection needed for transporting the anchor will inherently have a rating significantly higher than the anticipated loads during the deployment.



Nominal Size (in.)	Working Load Limit (t)*	Stock No.			Weight Each (lbs.)
		G-2130	S-2130	G-2130OC	
1-1/4	12	1019597	1019604	1262068	11.71
2	35	1019677	1019686	–	52.25

Dimensions (in.)									
A	B	C	D	E	F	H	L	M	N
2.03	1.40	4.69	1.29	3.25	3.00	8.25	5.75	6.69	1.38
3.25	2.30	7.75	2.08	5.75	4.81	13.68	10.15	10.81	2.40

Figure 25: Anchor Shackle Dimensions considered for connecting the anchor to the mooring line.

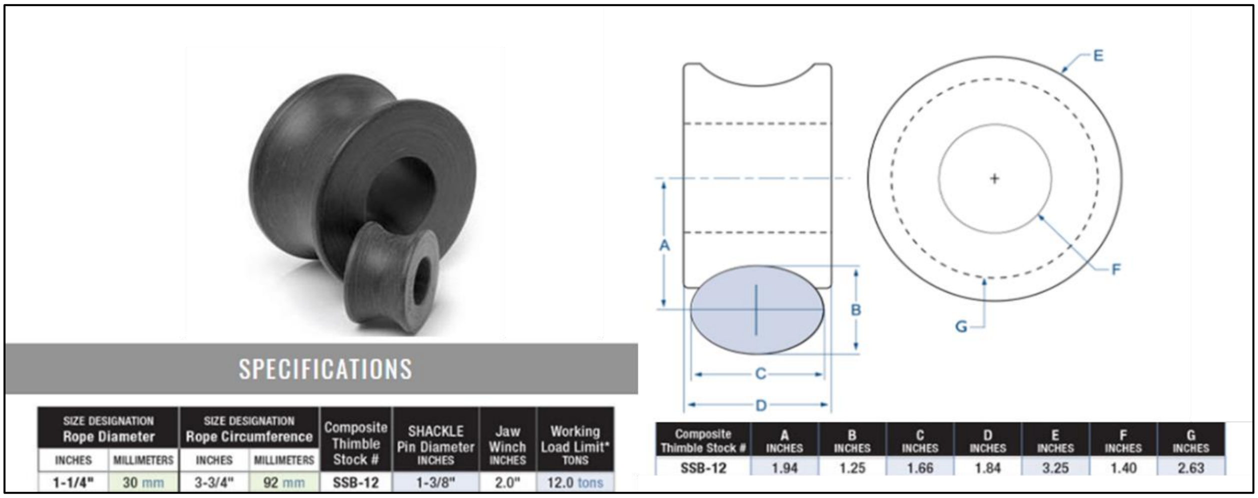
C.0200 Mooring Line

The mooring/tether lines will be comprised of two materials: 1) Belt and 2) Dyneema line, with spliced interconnector coupling the two. The decision to move to a belt rather than wire wrapping around the winch drum was because of concerns with the fatigue damage accumulation on the wire due to cyclic bending stress. A mooring line of braided Dyneema or similar High Modulus Polyethene (HMPE) will be used due to its high strength and stiffness properties, as well as its resistance to fatigue. The length of the mooring line required is determined based on the considerations discussed in the Mooring Report.

The mooring line will be spliced on both ends, with load applied to set the splice prior to commencing normal operation. However, it may not be possible to apply enough load to fully set the splices, therefore some minor loss of power production efficiency may be noticed in the first few cycles of operation until the splices are fully set.

Chafe Protection

For best protection against fatigue loading, a circular thimble has been chosen at both connection points instead of the more common teardrop style chafe gear. As these are not common stock items, they will need to be procured as fabricated items. To avoid corrosion, they are specified as 316 stainless steel, or composite. An example of a similar sized composite thimble is shown below;



SPECIFICATIONS

SIZE DESIGNATION Rope Diameter		SIZE DESIGNATION Rope Circumference		Composite Thimble Stock #	SHACKLE Pin Diameter INCHES	Jaw Winch INCHES	Working Load Limit* TONS
INCHES	MILLIMETERS	INCHES	MILLIMETERS				
1-1/4"	30 mm	3-3/4"	92 mm	SSB-12	1-3/8"	2.0"	12.0 tons

Composite Thimble Stock #	A INCHES	B INCHES	C INCHES	D INCHES	E INCHES	F INCHES	G INCHES
SSB-12	1.94	1.25	1.66	1.84	3.25	1.40	2.63

Figure 26: Example of Circular Thimble w/Dimensions

C.0300 Anchor

The anchoring system consists of four gravity anchors, which would be made from one of two options as identified in Table 4. Helical screw anchors are a technically feasible option but due to complications with permitting are no longer being considered for this demonstration. Discussions are on-going with anchor suppliers, vessel operators, divers and UCSD to determine the optimal solution. Figures below provide an overview of the WEC system with provisional anchor dimensions.

Table 4: Physical Characteristics of Gravity Anchor Options.

Physical Characteristic		
Anchor Type	Single Solid Concrete Block	Steel Frame & Concrete Block
Length	2750 mm	3000 mm
Width	3350 mm	3000 mm
Height	1400 mm	1500 mm
Mass	16.3T wet weight 30T dry weight	18.5T wet weight 35T dry weight
Substrate Compression	~300 - 600 mm	300 – 600 mm
Material(s)	Concrete	Steel and concrete
Surface Coating(s)	None	None

D-SCADA SUBCOMPONENTS

The WEC system is controlled via a master controller, with PTO primary controls based on environmental and system inputs. The SCADA system provides situational awareness and operator input capability. An overview of the SCADA is provided in Figure 27, and the components and functions of important subcategories are discussed below The backbone of the SCADA system is the EtherCAT network, in which the central controller exchanges data and commands in “real time” with a distributed array of input and output modules. Measurements are aggregated at the central controller, which defines actions to be taken to maximize energy capture, minimize loads, and ensure the safety of the platform.

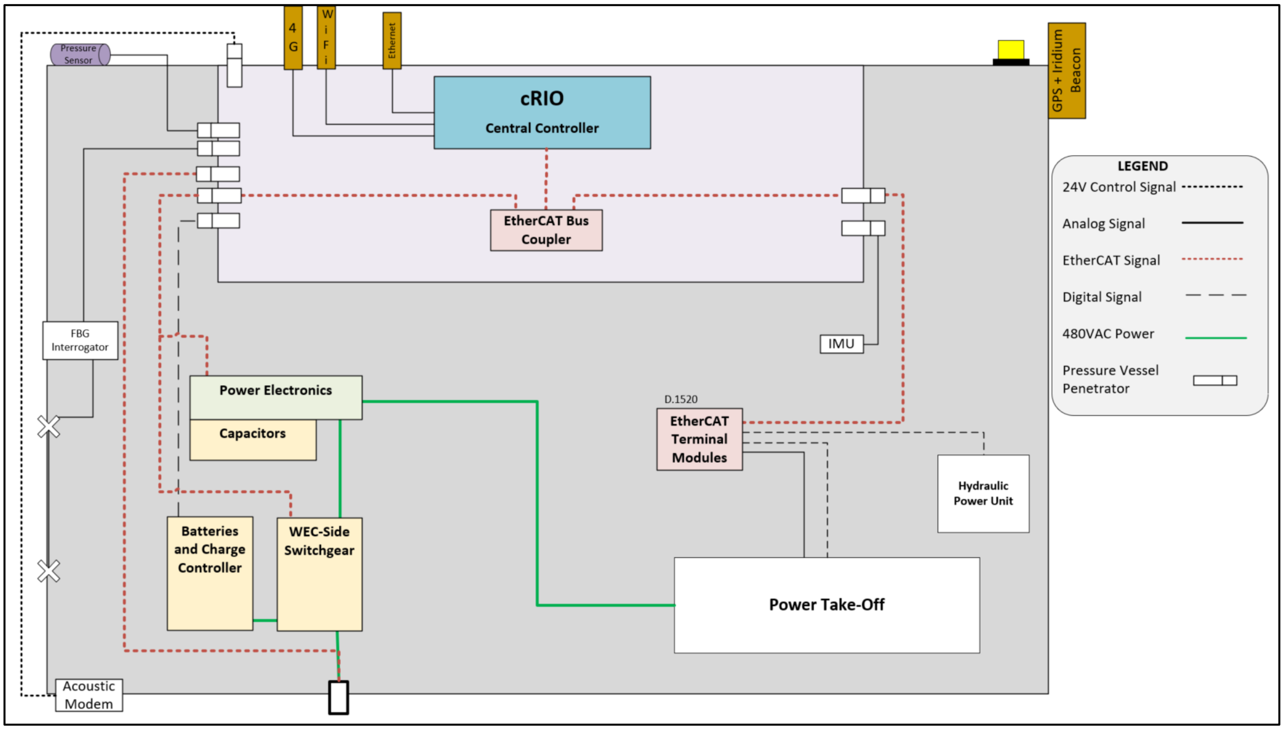


Figure 27: Simplified SCADA Layout.

D.0100 Hull Measurements

The hull's dynamic movements and position in the water column are a critical input for performance and safety. The Inertial Measurement Unit (IMU) blends data from an accelerometer, gyroscope, and magnetometer to define the WEC's attitude and dynamic motions. Pressure sensors on the hull's exterior measure the surrounding water pressure, providing both a depth measurement and recording the dynamic pressure changes as the device moves in the waves. Fiber Bragg Grating (FBG) sensors installed on the hull's interior structural members will measure tiny deformations due to wave loads.

D.0200 PTO Measurements – Electrical/Mechanical & D.0300 PTO Measurements - Hydraulic

The central controller communicates with the PTO via the EtherCAT network, wherein input modules collect measurement data for feedback to the controller and commands are output to the appropriate actuators or devices. The EtherCAT framework is modular, allowing many types of signals to be sent and received over a single communications bus. Among the PTO's mechanical and hydraulic components, analog sensor measurements are recorded and sent back to the central controller, which returns digital command signals to, for example, open a valve.

The electric motor/generator and power electronics have their own internal signal processing paths, operating on Siemens' proprietary ProfiDRIVE network. Cyclic data exchange between the Siemens power electronics and the WEC's central controller is via a special ProfiDRIVE – EtherCAT converter module. Real-time data exchange includes both measurements (voltages, currents, motor position, motor torque) and commands (current limits, torque setpoints).

D.0400 Communications

While the WEC is offshore it will operate autonomously, and remote communications will be the only means of changing its behavior. Multiple communications channels are maintained to provide redundancy and ensure some level of control is always maintained. The primary communication channel is via a fiber-optic cable embedded in the umbilical connection; this offers the highest data rate and can be used for real-time monitoring and adjusting of, for example, PTO control parameters. Unfortunately, if the umbilical is cut or otherwise interrupted, real-time communication with the submerged WEC will end. In this case the device will autonomously maneuver to survival depth, where it will remain in idle mode until a command is sent via acoustic modem that it is safe to rise to the surface. Once at the surface, fast wireless communications can be re-established using celluar or WiFi antennas.

E-ELECTRICAL PLANT SUBCOMPONENTS

The electrical plant describes the equipment needed to maintain a safe, stable electrical power connection within the WEC and between the WEC and the shore-side power supply. A simplified overview of the electrical plant components is shown in Figure 28.

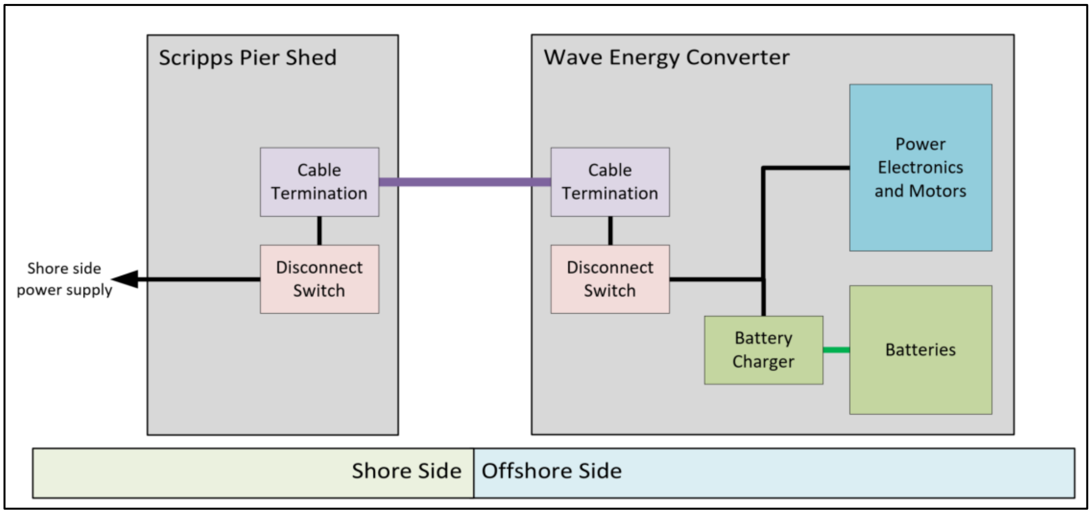
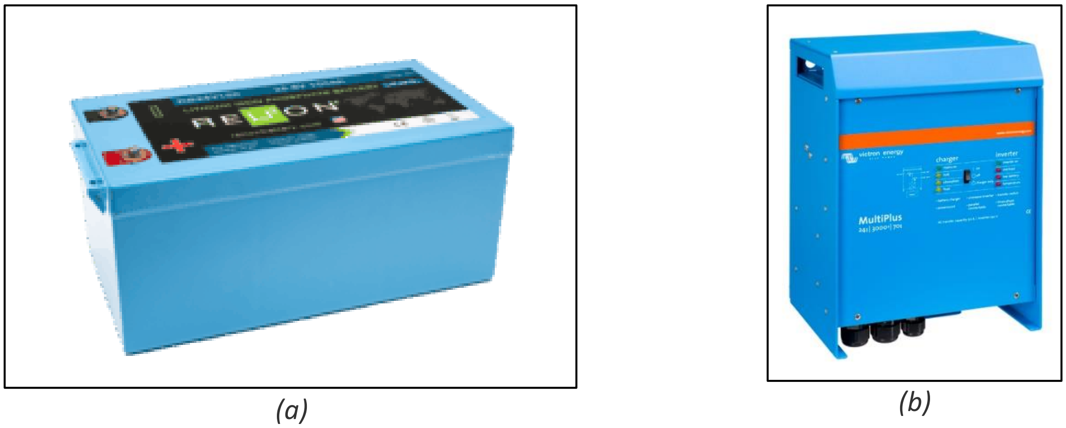


Figure 28: Schematic Overview of the WEC's electrical connection to the shore.

E.0100 Battery Energy Storage

Batteries onboard the WEC will provide power for critical components (controls computers, communications equipment) if the electrical connection from pier is interrupted, whether planned (during installation, maintenance, or recovery), or otherwise. The bank of Lithium-Iron-Phosphate ($LiFePO_4$) batteries will be sized to provide enough power to dive the WEC to safety depth, maintain controls and communications at full capacity for 4 days, and bring the device to the surface slowly and safely. A representative 24V, 100Ah battery pack, offered by ReLion, is shown on the left of Figure 29. On the right is a battery charger/inverter, offered by Victron Energy, which will be used to interface the 24VDC batteries with the 480VAC circuit onboard the WEC.



(a) (b)

Figure 29: Representative battery pack and charger/inverter.

E.0200 WEC-Side Switchgear

An umbilical cable will electrically connect the WEC to the on-shore power supply; see Section G for more details on the umbilical and terminations. A disconnect switch (pink box in Figure 28) onboard the WEC will enable isolation of the WEC's internal 480VAC circuit from the cable connection during installation, maintenance, and recovery.

E.0300 Shore-Side Switchgear

A matching disconnect switch (pink box in Figure 28) will be located on the pier, immediately after the umbilical cable termination, allowing the WEC to be isolated from shore without any need for marine operations.

F- AUXILIARY SYSTEMS SUBCOMPONENTS

F.0100 Navigational Aids

The CalWave demonstration WEC device would be deployed about 1,800 feet offshore away from the Scripps pier (Figures 3, 4, and 6). Aids to navigation in the form of marker buoys including night-visible lighted beacons would be employed to ensure the project doesn't present a hazard to vessels in the area. Two marker buoys of 1.5 feet diameter, yellow color, yellow flashing light with 6s period, or other appropriate marker buoys per USCG Aid to Navigation Manual would be tethered and located vertically above the southwest and northeast anchors. Navigational lighting—flash rate, sequence, color and intensity—would comply with United States Coast Guard instructions, including dimensions and materials. It is currently envisioned that these marker buoys would be tethered to the same anchors as the CalWave demonstration WEC, described above. However, if the potential of line entanglement becomes a concern as anchor system detailed design evolves, it may instead be preferred to use additional suitably sized (relatively small) anchors for the marker buoys.

F.0200 Bilge

An active bilge system is not planned for this demonstration. The WEC internal frame layout in the WEC hull allows for a natural collection point for any condensation or fluids between stiffeners. The available volume in this bilge space greatly exceeds any anticipated fluid accumulation. Bilge grating is intended to cover these spaces to minimize movement of any accumulated fluid from out of the bilge spaces during WEC dynamic motions.

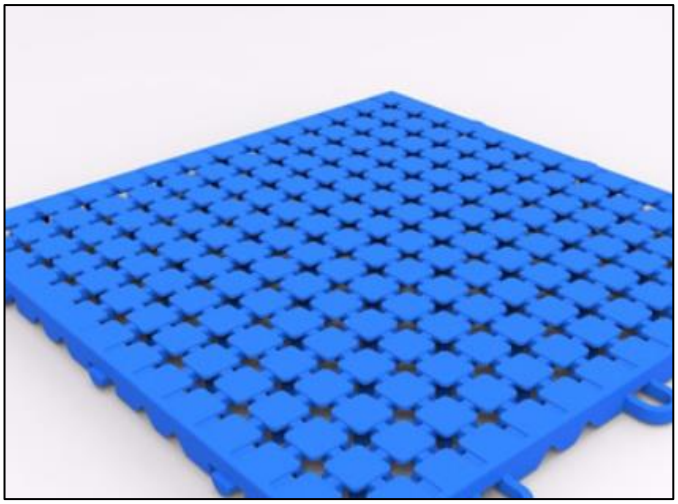


Figure 30 Example bilge grating.

F.0300 Hydraulic System

A schematic of the WEC supporting hydraulic system is shown in Figure 31. A single Parke H-Pak hydraulic power unit (HPU) provides hydraulic power to all of the various hydraulic consumers in the WEC, including the PTO gas spring, clutch, and brake. Various directional spool and cartridge valves control flow from the HPU to the various components. An intermediate accumulator stores hydraulic energy and allows the HPU to run intermittently. A pressure reducing valve maintains pressure to the hydraulic break and clutch at 103 bar regardless how much higher the pressure in the intermediate accumulator gets. Manual flow control valves are set during commissioning to set the brake engage and gas spring accumulator discharge at reasonable rates. Manual ball valves ensure that the system can be safely depressurized even if in the event of a digital valve failure. Various pressure sensors are used to monitor the hydraulic system status. A preliminary hydraulic support system that was assembled to support PTO test stand experiments can be found in Figure 32.

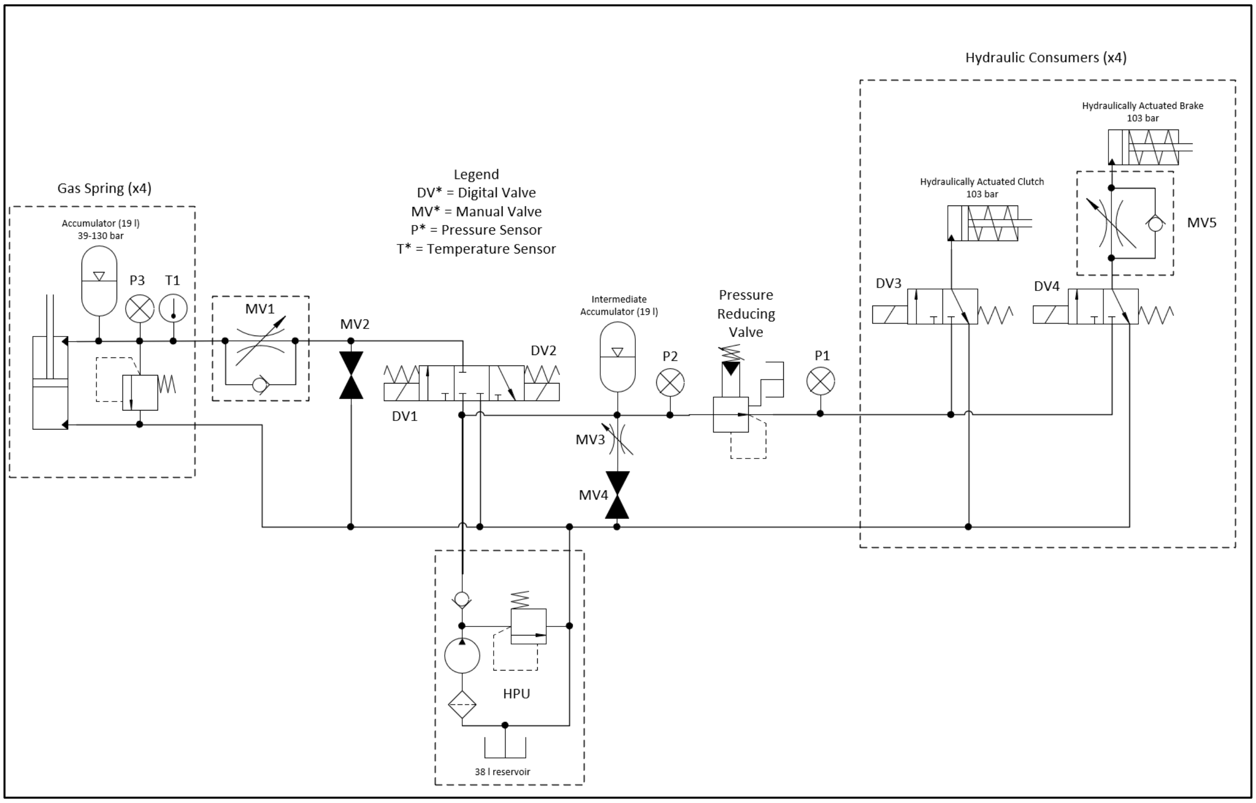


Figure 31: Hydraulic system circuit schematic.

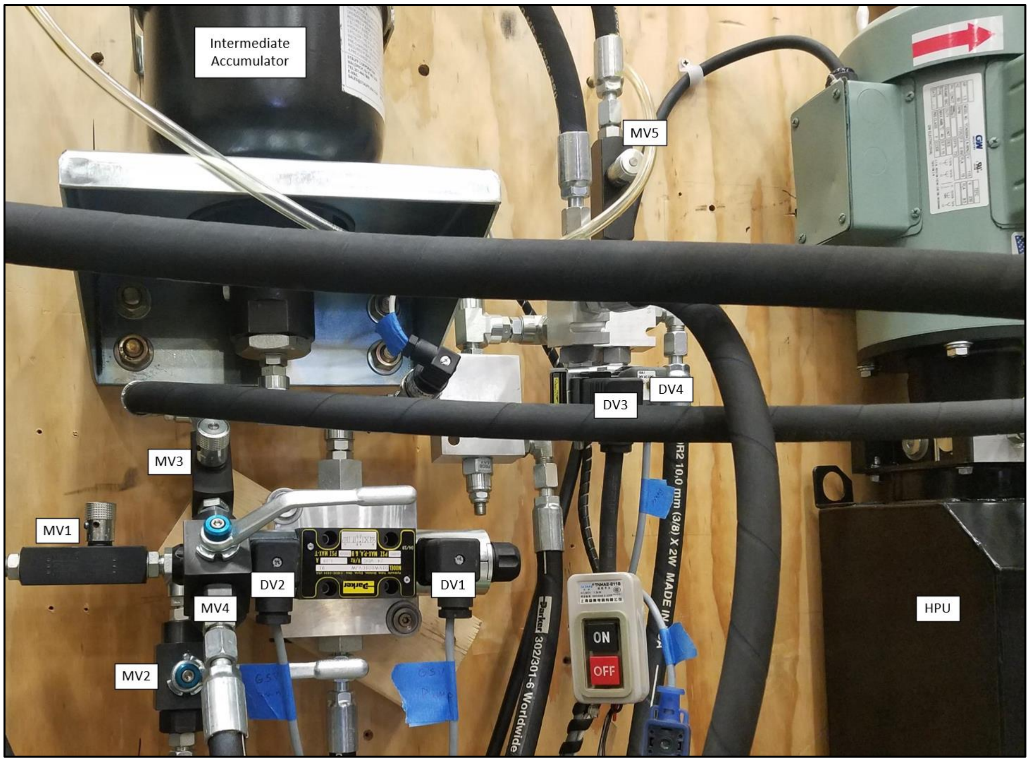


Figure 32: Preliminary hydraulic support system assembled to support PTO test stand.

F.0400 Climate Control

Based on the surface area of the WEC hull in contact with the ocean, it has been determined that sufficient convective cooling exists, and an external cooling system are not required. However, it is important to ensure condensation or high humidity does not exist in the vicinity of the power electronics or other electrical equipment. To avoid this, humidity and temperature sensor are added in electrical enclosures that control local heaters to keep ambient temperature near electrical equipment above the dew point.

F.0500 Data Logging

Real-time data traffic will pass from the WEC to the shore-based SCADA to provide situational awareness and control input ability to an operator; and quickly identify unexpected events. Data will be logged within the SCADA for initial, local, post processing. Periodic uploads to the CalWave server in Oakland, California will provide for more in-depth post processing. Additionally, data is logged locally on the WEC to provide a backup in the case of issues with the umbilical cable or pier side SCADA.

G-UMBILICAL SUBCOMPONENTS

One umbilical cable will run between the CalWave demonstration WEC and the shore-based facility.

G.0100 Export Cable

The umbilical cable would be rated for a 600-volt maximum capacity and carry an average of 5 kW and peak of 10 kW power. The umbilical cable is approximately 1” in diameter, protected by double sheathed polyurethane and a Vectran strength member (Table 5). Due to the relatively low voltage and power level, it is not believed that shielding is required.

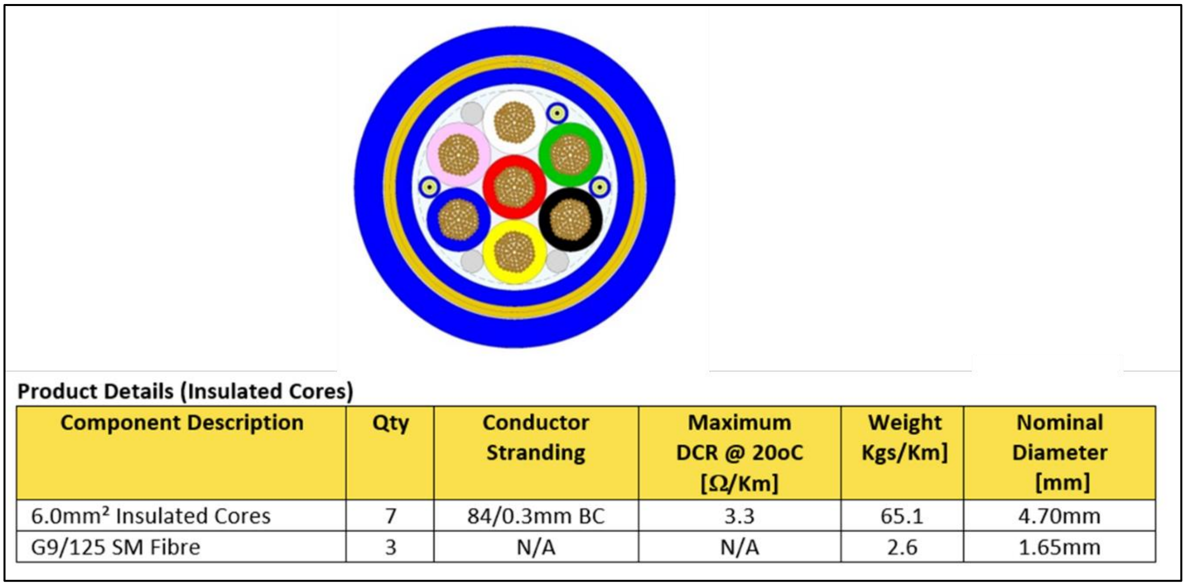
Table 5: Umbilical cable Physical Characteristics.

Physical Characteristic	Measurement
length	~600 m
diameter	~30 mm
trench width	no trench used, dead weights on cable
trench height	no trench used, dead weights on cable
burial depth	no trench used, dead weights on cable

For this deployment, several umbilical cable manufacturers were consulted and various options for umbilical cable form factor and specifications were reviewed. Steel armoring was determined not to be required for electrical shielding purposes or for structural integrity. This is due to the soft sandy seafloor at the deployment site, the anticipated dynamic motion of the umbilical, and weight and size considerations for deployment.

The currently anticipated linear distance of the umbilical cable travel, from SIO pier to the test site, is 1823 ft (556 m). The final determination of cable distance will be dependent on the anchor site survey and marking operation. Lead time for the umbilical cable (including connector fitting) is 16 weeks, which provides some schedule margin for the anchor survey to be completed immediately upon receipt of site permits and progression to budget period 2. Should significant delays occur in required permitting for the anchor site survey, the umbilical cable lead time will need to be considered. A risk mitigating work around in such case would be to order sufficient additional length of umbilical cable to accommodate some level of adjustment in anchor placement due to unanticipated seafloor obstructions or other considerations.

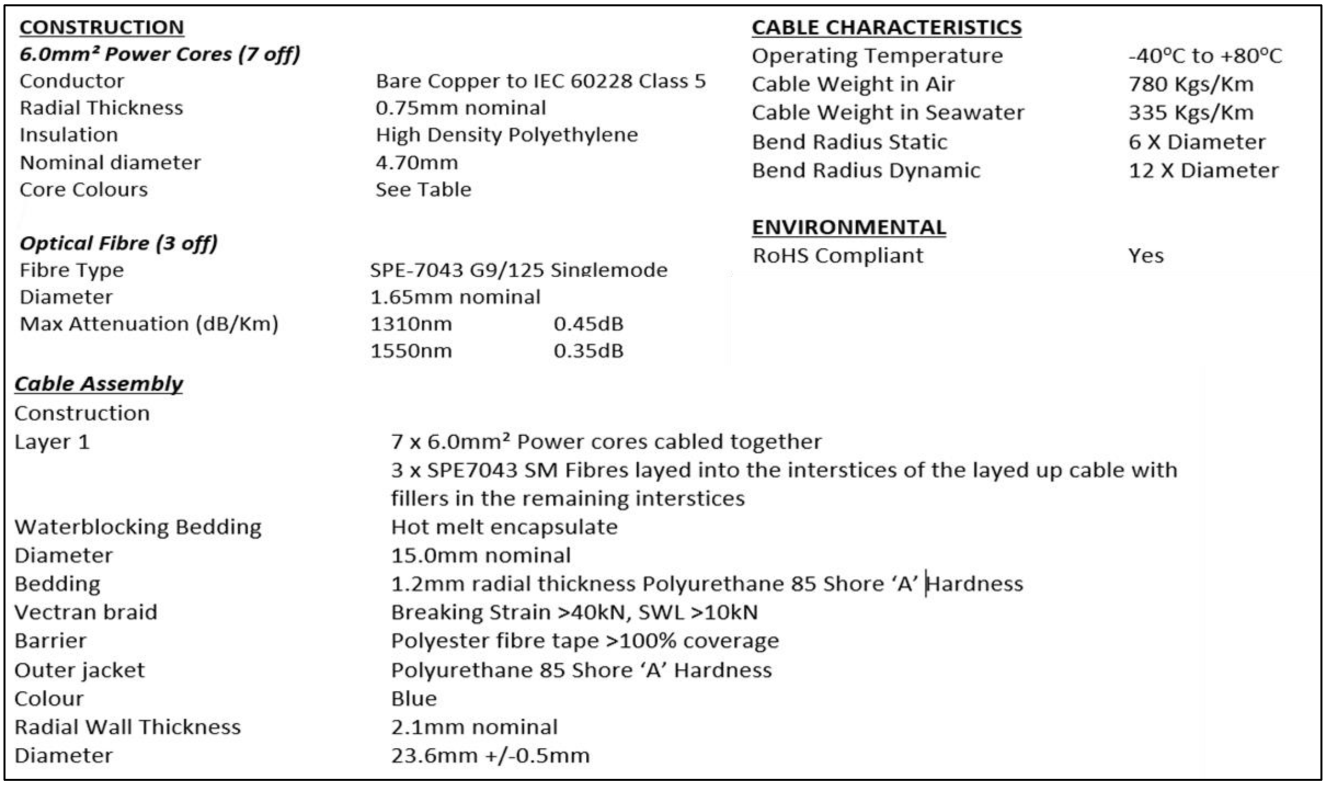
The selected umbilical cable is rated for 600V and consist of seven insulated power cores sized at 6mm^2 (~10 AWG), three single-mode fiber optics, and Vectran braid strength member. Cable specifications are provided in the figures below;



Product Details (Insulated Cores)

Component Description	Qty	Conductor Stranding	Maximum DCR @ 20oC [Ω/Km]	Weight Kgs/Km]	Nominal Diameter [mm]
6.0mm² Insulated Cores	7	84/0.3mm BC	3.3	65.1	4.70mm
G9/125 SM Fibre	3	N/A	N/A	2.6	1.65mm

Figure 33: Umbilical Cable.



CONSTRUCTION

6.0mm² Power Cores (7 off)

Conductor	Bare Copper to IEC 60228 Class 5
Radial Thickness	0.75mm nominal
Insulation	High Density Polyethylene
Nominal diameter	4.70mm
Core Colours	See Table

Optical Fibre (3 off)

Fibre Type	SPE-7043 G9/125 Singlemode	
Diameter	1.65mm nominal	
Max Attenuation (dB/Km)	1310nm	0.45dB
	1550nm	0.35dB

CABLE CHARACTERISTICS

Operating Temperature	-40°C to +80°C
Cable Weight in Air	780 Kgs/Km
Cable Weight in Seawater	335 Kgs/Km
Bend Radius Static	6 X Diameter
Bend Radius Dynamic	12 X Diameter

ENVIRONMENTAL

RoHS Compliant	Yes

Cable Assembly

Construction	
Layer 1	7 x 6.0mm² Power cores cabled together 3 x SPE7043 SM Fibres layed into the interstices of the layed up cable with fillers in the remaining interstices
Waterblocking Bedding	Hot melt encapsulate
Diameter	15.0mm nominal
Bedding	1.2mm radial thickness Polyurethane 85 Shore 'A' Hardness
Vectran braid	Breaking Strain >40kN, SWL >10kN
Barrier	Polyester fibre tape >100% coverage
Outer jacket	Polyurethane 85 Shore 'A' Hardness
Colour	Blue
Radial Wall Thickness	2.1mm nominal
Diameter	23.6mm +/-0.5mm

Figure 34: Umbilical Cable Specifications.

G.0200 Connectors

The connector and termination solution will consist of a molded breakout which separates the strength member from the electrical components and directs into a clevis & pin style strain termination (pictured below). Connectors for the power cores and fiber optics will be separated out in the molded strain termination. This allows for the connector and WEC hull bulkhead penetration to be removed from any mechanical loading on the umbilical cable. Due to the shallow freeboard of the WEC when in floating position (~600-900 mm) and the need for using dry-mate connectors (wet-mate connectors were found to be prohibitively expensive), it is envisioned that the bulkhead connector on the WEC side will be located on the top of the WEC hull. This will also help to minimize relative motion between the small boat tied to the WEC and the WEC itself and provide for the safest possible operations when connecting and disconnecting the umbilical cable from the WEC. The figures below present the strain termination, in-line connectors and WEC side bulkhead connectors. Discussions are on-going with the manufacturer to replace the shown in-line connectors with right angle connectors. All dimensions are in mm unless otherwise specified.

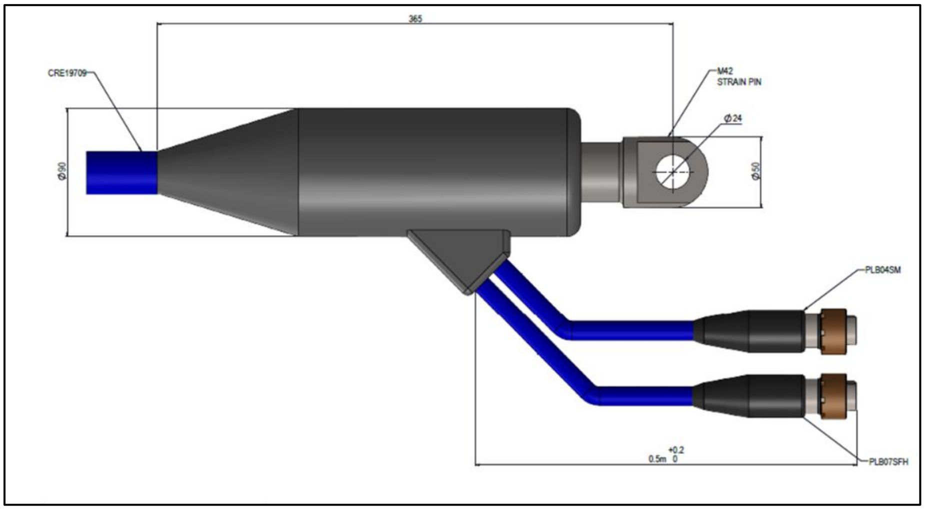
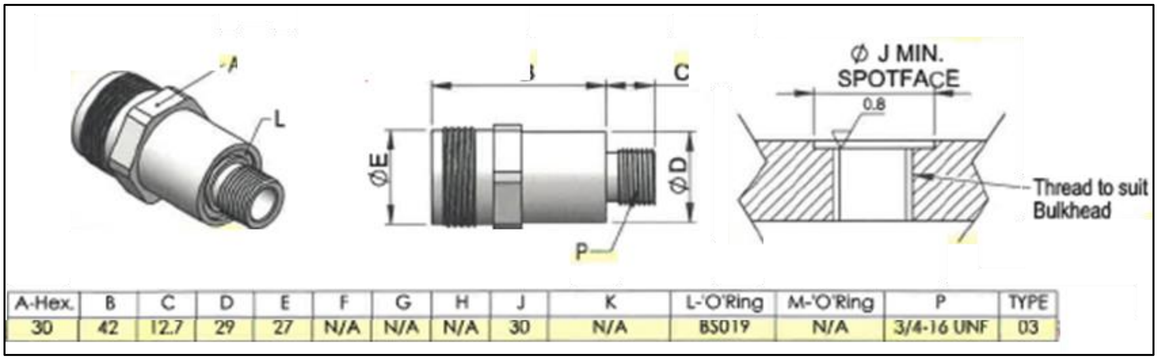
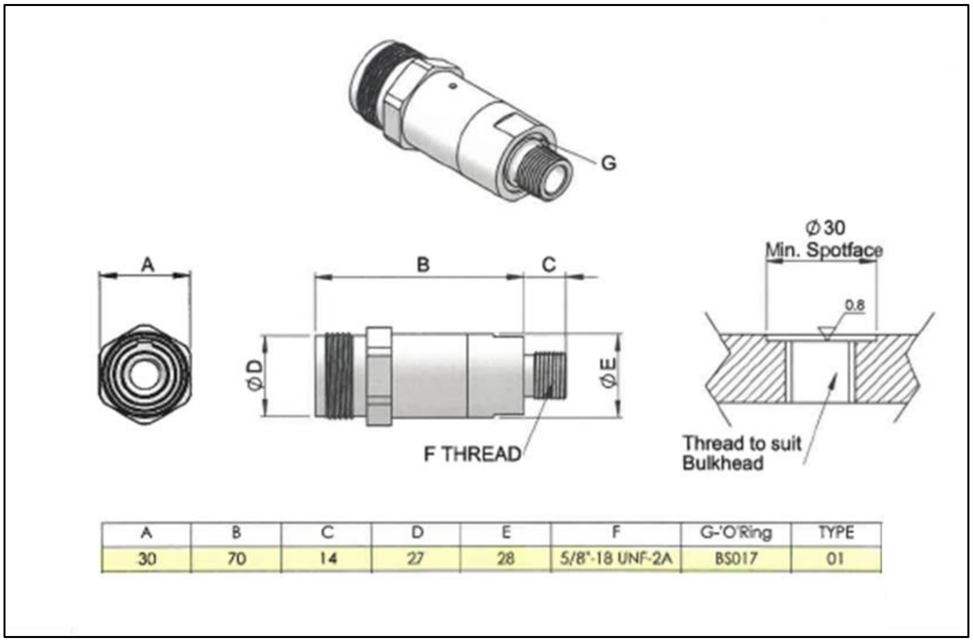


Figure 35: Umbilical Strain Termination w/ in-line connectors (dimensions in mm).



A-Hex.	B	C	D	E	F	G	H	J	K	L-'O'Ring	M-'O'Ring	P	TYPE
30	42	12.7	29	27	N/A	N/A	N/A	30	N/A	BS019	N/A	3/4-16 UNF	03

Figure 36: Umbilical Power Bulkhead Connector (BR).



A	B	C	D	E	F	G-'O'Ring	TYPE
30	70	14	27	28	5/8"-18 UNF-2A	BS017	01

Figure 37: Umbilical Fiber Optic Bulkhead Connector – BR.

The below figure illustrates how the umbilical is envisioned to be connected to the WEC. In this figure the in-line connectors have been replaced with right angle connectors. O-rings are specified as standard BS017 & BS019 nitrile; however further investigation into sealing specifications for bulkhead connectors is planned for budget period 2.

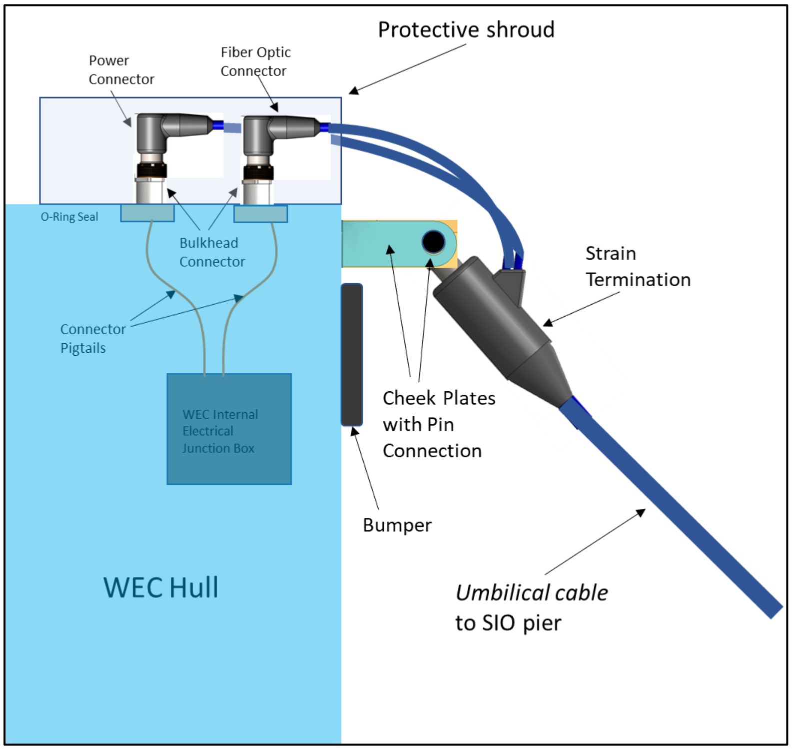


Figure 38: Umbilical Termination.

G.0300 Cable Seakeeping and Anchoring

During deployment of the umbilical cable, sandbag weights will be attached to the umbilical at periodic intervals to ensure the umbilical position is maintained. The deployment area has minimal currents and will require only small anchors. An example of a sandbag that may be used as an umbilical cable anchor is pictured below.

Figure 39: Umbilical Cable 15-lb Sandbag Anchor.

The dynamic section of umbilical cable that lifts from the seafloor and connects to the WEC will include a Lazy S configuration. This will ensure the umbilical cable is kept away from the mooring lines and avoid entanglement. Creating this Lazy S involves including a sufficiently sized cable anchor where the umbilical lifts off the seafloor to prevent the static section of the umbilical from being pulled toward the WEC and attaching buoyancy modules to ensure the shape of the Lazy S is maintained. In addition, abrasion protection will be added to the umbilical cable at section where chafing is likely. For this deployment, it is anticipated to use spiral wrap as chafe protection.