Test Plan

xWave New Technology Qualification and Path to Certification

Awardee: CalWave Power Technologies Inc.

Awardee point of contact: Thomas Boerner

Facility: American Bureau of Shipping

Facility point of contact: Shirlyn Zhang

Date: 10/31/2022

1 Executive Summary

This document outlines the test plan and results for the New Technology Qualification (NTQ) process of CalWave's xWave wave energy converter (WEC) technology by American Bureau of Shipping (ABS). Main objective of the TEAMER project was to evaluate the xWave's feasibility and concept verification stages based on existing data, reports, and risk management efforts, and to identify a roadmap for further development and certification.

CalWave's xWave WEC technology is a fully submerged WEC that utilizes pressure differentials from ocean waves to generate electricity through multiple, independently controlled power take-off (PTO) units. The technology merges several load management features such as drivetrain detuning, load management via geometry control, and load management via submergence control and is designed according to IEC/IEEE standards.

Main tasks concluded throughout the project were the independent review of xWave's maturity level that will ultimately increase confidence for investors, partners, and regulatory agencies. Throughout the project, ABS reviewed review CalWave's design documentation, operational planning, and risk assessment. Feedback was collected and discussed in multiple iterations. ABS's review process focused on the two first stages of the NTQ process, namely the "Technology Feasible" and "Concept Verified" stages.

The project was successfully completed and CalWave received the Statement of Maturity for the "Technology Feasible" and "Concept Verified" stage. The project conducted under this TEAMER award will further benefit CalWave by paving the way for future certification steps in the NTQ stage-gate process.

2 INTRODUCTION TO THE PROJECT

CalWave is developing a wave energy converter (WEC) called xWave, which operates fully submerged and is classified as a submerged pressure differential type. As ocean waves pass over the submerged wave buoy, a pressure differential is created, exciting the absorber in multiple degrees of freedom to oscillate in resonance with the ocean waves. Energy is efficiently extracted using multiple independently controllable power take-off (PTO) units. Based on CalWave's 2 body WEC technology tested in the US DOE's Wave Energy Prize, multiple improvements on absorber geometry and PTO controls have been achieved.

CalWave has developed advanced WEC control algorithms that can significantly enhance the device’s power absorption as well as safe operation during the past three years. The advanced controls have been developed using extensive numerical modeling in the frequency and time domain and implemented in controller at 3 separate wave tank tests (total of 6 weeks testing). In parallel with the core hydrodynamic and control development, CalWave has progressed on associated anchoring, mooring, umbilical cable, grid interconnection, and operations and maintenance development. This co-development is aligned with the holistic approach to system development.

A critical aspect of achieving commercial deployments for the xWave, or any new grid integrated technology, is the formal certification. Achieving certification for a new technology is a dedicated multi-year process that ultimately provides the confidence needed to allow for wide scale insurability and bankability of commercial scale systems. As CalWave progresses the xWave technology through iterative scaled deployments, integrating this development with a structured and formalized certification process will be foundational not only to CalWave’s success, but also to the advancement of the marine energy industry by providing working reference cases of certified systems and growing confidence within the industry, leading to increased participation of utility operators and unlocking project financing opportunities.

ABS (the Facility) will provide New Technology Qualification (NTQ) support for the WEC designed by CalWave, based on the processes outlined in the ABS Guidance Notes on Qualifying New Technologies for the maritime industry. ABS will provide statements of maturity at each stage of the development, which will support the commercialization of the technology.

3 Roles and Responsibilities of Project Participants

3.1 Applicant Responsibilities and Tasks Performed

CalWave will provide design documentation, operational planning, and risk assessment for the patented xWave technology that will form the foundation of the New Technology Qualification process. At each stage of the review, CalWave will work in collaboration with ABS to incorporate feedback into revised product design, operational planning, and risk assessment documentation that is aligned with the prototype validation process. Additionally, CalWave will ensure iterative feedback obtained during the NTQ process will be fed into further development goals and planning to best align the xWave technology development with the ABS guided validation roadmap.

Network Facility Responsibilities and Tasks Performed

ABS will conduct New Technology Qualification of the proposed design and issue statements of maturity for each stage of the qualification process. The Statements of Maturity issued at each stage will demonstrate feasibility and maturity levels as evaluated by ABS based on its unique role in the industry. Typically, five sequential steps will be taken for the NTQ process, which progressively qualify the technology from the feasibility stage, concept verification, prototype validation, system integration through the operational stage (see Figure 1). The qualification activities within each stage revolve around risk assessments and engineering evaluations that build upon each other to determine if the new XWave system provides acceptable levels of performance and safety in line with established requirements and current marine industry practice. In this project we will focus on the feasibility and concept verification stages only based on the existing testing and numerical data. We will work with CalWave to continue with the NTQ process of prototype validation based on newly developed testing data in 2022. This is out of the scope of work in the current Teamer project.

While the NTQ process will be applied specifically to CalWave’s WEC technology in this project, the disseminated results will benefit the broader community. The community will know that the XWave WEC technology has been subjected to an independent review and assessment of the maturity of the system with formal correspondence issued confirming the system’s ability to perform intended functions in accordance with defined performance requirements. The marine renewable energy industry routinely develops new technologies with no service history in the proposed application or environment. There is often a period of time when the technology is still a concept design or a mockup of the future full-service device. During this time, it is difficult for the designers to judge if the technology is still worth future efforts or investment. ABS’ NTQ could be especially valuable in walking the designer through the early stages and help improve the technology through various maturity levels.

The NTQ Process will provide CalWave, its customers/partners, funding entities, and other interested parties (Government agency Technical Authorities, regulators, insurers, etc.) with a high degree of confidence that the resulting technology is mature and robust enough for the intended applications. Through Statements of Maturity issued at each stage in the qualification process, regulatory agencies can be confident that foreseeable hazards associated with the introduction of the proposed new technology have been systematically reviewed by a reputable third-party.

After completion of the project, we will deliver a post access report with two Statement of Maturity letters for new technology.

4 PROJECT OBJECTIVES

The project objective is to review CalWave's innovative design, and to verify the new system will perform its functions in accordance with defined performance requirements on feasibility and concept verification stages. As an outcome of the process, Calwave intends to present results in a scholarly publication.

The design documentation being reviewed in the NTQ process includes the following critical components, tools, and analysis:

- xWave Design Basis & Regulatory Guidance
- System Modelling and Design Tools
- Absorber Body Design
- Power Take-Off Design
- Electrical System & Infrastructure
- Umbilical Design
- Mooring and Anchoring Design
- xWave Operational Design for PacWave (including Power Performance)
- Installation, Operation & Maintenance
- Risk Management & FMECA
- Outstanding Testing for Validation
- System requirements and description document (SRDD)

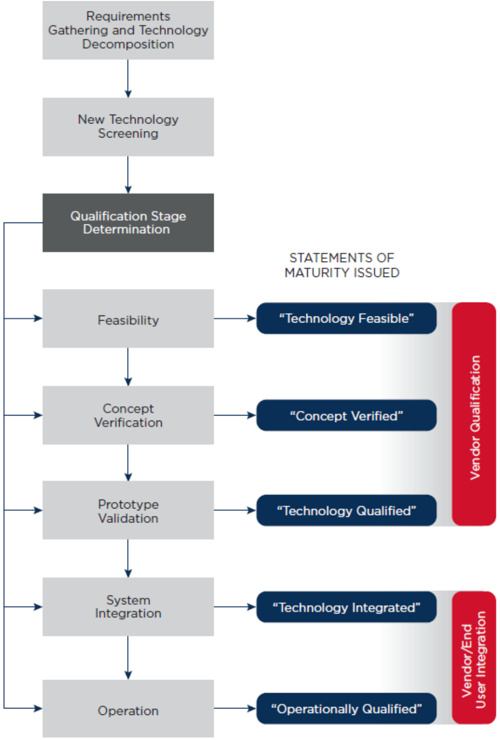


Figure 1. ABS New Technology Qualification Process

5 TEST FACILITY, EQUIPMENT, SOFTWARE, AND TECHNICAL EXPERTISE

ABS is a not-for-profit marine classification, standards, and technology organization head quartered in the United States of America. ABS has over 3,000 engineers, scientists, and marine surveyors with global expertise in the design, installation, operation, and maintenance of all types of marine and offshore assets. ABS provides a wide range of engineering analysis, modeling, and simulation support for the marine energy sector. The support includes hydrodynamic modeling of wave and flows movements, structural analysis of marine energy equipment, mooring analysis, system reliability, safety modeling and verification. ABS also provides third party independent verification/validation of marine energy systems under ABS' New Technology Qualification (NTQ) and Approval-In-Principle (AIP) processes. ABS is actively involved in the industry technical committee such as IEC renewable energy working group. ABS has partnered with many private companies and academic institutions in supporting their development of marine energy technologies.

Dr. Xi-Ying Zhang and Mr. Jude Tomdio from ABS will lead the NTQ process in this Teamer project. Dr. Xi-Ying Zhang is Principal Engineer at ABS Corporate Technology Department, Houston, Texas. She has 15 years of experience in the offshore industry and specializes in offshore structures and geotechnics, mooring and anchor systems. Currently she is the technical lead for marine energy projects at ABS. She has participated in the development and revision of industrial codes of practice and ABS Rules/Guides/Guidance Notes for marine and offshore applications.

Mr. Jude Tomdio is currently Principal Engineer for the machinery, propulsion, electrical and controls technologies. Mr. Tomdio has over 15 years of experience and his areas of expertise include electrical, instrumentation and control technologies, advanced power systems, AC and DC electrical networks, energy storage systems, renewable energy sources, risk assessment, electrical safety and hazardous area classification, classification review/verification, and qualification processes.

6 Test or Analysis Article Description

CalWave is developing a wave energy converter (WEC) called xWave, which operates fully submerged and is classified as a submerged pressure differential type. As ocean waves pass over the submerged wave buoy, a pressure differential is created, exciting the absorber in multiple degrees of freedom to oscillate in resonance with the ocean waves. Energy is efficiently extracted using multiple independently controllable power take-off (PTO) units.

CalWave's *xWave* WEC technology is designed according to IEC/IEEE and to address the biggest challenges in ocean wave energy: Extreme loads in stormy seas, and consistent, reliable power output. The xWave consists of a single absorber body housing individually controlled PTO units that connect to taut mooring legs. The absorber oscillates fully submerged and is capable of true multi-DOF (Degree of Freedom) power absorption with significant efficiency increase. Below images show the currently deployed scale model WEC as deployed on the ocean surface (left) and operating submerged (right). The xWave architecture enables critical and redundant load management approaches via:

1. PTO detuning,
2. variable submergence depth, and
3. proven unique geometry-changing control mechanisms.

CalWave has developed advanced WEC control algorithms that can significantly enhance the device power absorption as well as safe operation during the past three years. The advanced controls have been developed using extensive numerical modeling in the frequency and time domain and implemented in controller both in multiple iterations of wave tank testing and PTO bench testing. CalWave's xWave technology can be operated in a variety of resources due to its large bandwidth enabled by Holistic Controls and is entirely scalable in its approach. Primarily mid-term application at intermediate scales is targeted as utility scale grid operators, community choice electricity authorities (CCA's) and coastal communities.

CalWave intends to initially focus our development where we can have the most impact: island communities, which make up 11% of the world's population (730 million). Over 90% of power on islands is generated through imported fossil fuels, which creates a huge burden on developing economies and the environment. By offsetting these communities' reliance on costly, heavily polluting diesel generation, we can make significant gains towards reducing global greenhouse gas (GHG) emissions and bringing equity to all. The 18.7 million people living in the Pacific Islands and New Zealand have an estimated combined electricity consumption of over 46 GWh/yr.

Similarly, Alaska, Hawaii, and Puerto Rico consume 45 GWh/yr of electricity which can be provided by wave power technology. These entry-level markets are not only the most commercially attainable due to the high cost of imported energy, but they are also most impacted by the effects of climate change.

7 WORK PLAN

7.1 NTQ DESCRIPTION

In this application, ABS will review the following documents and issue statements of maturity regarding the technology developed by Calwave:

- Wave tank and bench test data in FOA-1663,
- Larger scale PTO development and bench testing in FOA-1837, and
- Calwave design report for PacWave in FOA-2080.

Using them as a baseline for establishing a formal path to certification, Calwave will continue its future design development after completion of these FOAs.

For this specific project, ABS will perform the following activities:

New Technology Requirements Gathering and Technology Screening
The NTQ follows a system engineering approach to qualifying new technology. The qualification process starts with a top-down system decomposition, wherein the system is divided into subsystems, which are further broken down into components. The decomposed system should be reviewed to identify which of those items are considered new technology. Once the system is decomposed into subsystems/components, the system requirements can be mapped to each item. A system requirements and description document (SRDD) will be developed by Calwave for the new technology and submitted to ABS for review. It will be maintained throughout the NTQ process. This document defines and sets the baseline requirements for the new technology. As the design matures through development and as more knowledge is gained through qualification, these requirements may be subject to change.

New Technology Qualification Plan
The NTQ Plan defines a roadmap for progressing the new technology through the appropriate qualification stages. The objective of the plan is to provide a summary of qualification activities that need to be performed at each stage in order to demonstrate the ability of the new technology to meet the requirements specified in the SRDD. The initial plan should be developed based on the findings in the screening process. The plan is updated at each subsequent stage based on the findings from the previous stage and discussions between Calwave and ABS.

Stage 1 – “Technology Feasible”

ABS will perform a high-level review of:

1. Design basis, functional specification, and technical specification of the Xwave system.
2. System and function architecture details, such as functional flow block diagram if any.
3. Design details such as basic engineering drawings and engineering principles associated with further development.
4. Software tool- review of validation test data (as requested), and test results
5. Design analysis methodology and any available preliminary results, e.g. hydrodynamic analysis, device dynamics and kinematics modeling, PTO modeling, electrical system modeling and umbilical modeling.
6. Details regarding physical and functional interface requirements (mechanical, electrical, software, etc.).
7. Applicable design references, codes, standards and guidelines, and technical justification for any proposed deviations.
8. Risk assessment study developed by Calwave

Stage 2 – "Concept Verified"

The second stage of the NTQ process is the Concept Verification Stage. This is accomplished by performing more detailed engineering studies and physical model testing. ABS will:

1. Review documents that describe the concept verification design requirements.
2. Review design documents that include but not limited to the configuration, drawings, analytical models, etc.
3. Review preliminary manufacturing plan, initial test plan and test results.
4. Review testing in PacWave and PacIsland. Verify if the XWave system at a conceptual level satisfies the specified functional and performance requirements. The performance requirements are to be established by Calwave and should be detailed enough that the technology can be evaluated against the expected performance criteria.
5. Review updated risk assessments from the feasibility stage and preliminary design risk assessment (e.g., FMECA) report.

7.2 TEST AND ANALYSIS MATRIX AND SCHEDULE

The budget hours for this project are 160 hours. We will complete all the tasks in 8 weeks' time. We present a test plan as follows with the proposed schedule.

	Month 1				Month 2			
Tasks	Week 1	2	3	4	5	6	7	8
Calwave - Collect design reports/industry standards	▨							

Calwave - Develop system requirements and description document (SRDD)		■						
ABS/Calwave to Develop NTQ plan		■						
ABS to review reports and give comments for Stage 1 “Technology Feasible”			■	■				
Calwave to address comments for Stage 1					■			
ABS to review reports and give comments for Stage 2 “Concept Verified”					■	■		
Calwave to address comments for Stage 2							■	
ABS to develop post access report with letters of maturity							■	■
ABS to Post Access Questionnaire								■

7.3 SAFETY

The mission of ABS is to serve the public interest as well as the needs of our clients by promoting the security of life and property and preserving the natural environment. ABS is committed to excellence in environmental, health and safety management. ABS promotes a safe and healthy environment for staff and visitors, through programs and practices designed to protect people and the environment.

The ABS staff will follow all relevant safety procedures and protocols outlined at ABS Health, Safety, Quality, Environmental (HSQE) SharePoint https://eagle.sharepoint.com/sites/Intra/hsqe/SitePages/Home.aspx (internal access only).

In early 2020, ABS became increasingly concerned with enforcing sanitization in the office space to protect employees from COVID-19. Since March 2020 ABS employees have been working from home. There is a dedicated team from ABS making every effort to proactively monitor the situation and ensure a safe working environment for all ABS employees. Since all proposed work will be performed on the computer, the safety or health risks for the project will be minimal.

7.4 CONTINGENCY PLANS

ABS will have two additional engineers who are qualified to support the proposed project during the project time. The manpower will be more than sufficient to carry out the project to completion.

7.5 DATA MANAGEMENT, PROCESSING, AND ANALYSIS

7.5.1 Data Management

During the project, ABS will provide a secure data management environment for collaborative work among project team members. Our team will store and maintain the data in the Microsoft (MS) Teams environment with integrated MS Office applications. Microsoft OneDrive will be used to keep data and files backed up, protected, synced, and accessible on all our devices. This OneDrive app lets us view and share OneDrive files and documents with all team members.

The ABS IT department maintains appropriate cybersecurity controls consistent with the U.S. Government Risk Management Framework for cybersecurity and other IT-security requirements. We will be glad to provide additional information on these controls as requested.

The following table summarizes the management plan for specific project data. The final post-access report and all the relevant data (both meta and raw) to support the output figures, tables, and graphs presented in the Final Post Access report in connection with the implementation of the Project Documents will be submitted to MHK-DR and be publicly available.

Type of Data	Access to Data
Calwave Design Reports	This data will only be used within the project team. No outside access will be provided.
A system requirements and description document (SRDD) which defines and sets the baseline requirements for the new technology	SRDD will be included in the Final Post Access report and be publicly available.
New Technology Qualification Plan which defines a roadmap for progressing the new technology through the appropriate qualification stages	NTQ plan will be included in the Final Post Access report and be publicly available.

Review comments from ABS for Stage 1 “Technology Feasible” and Stage 2 “Concept Verified”	Review comments will be included in the Final Post Access report and be publicly available.
Responses to comments from CalWave for Stage 1 “Technology Feasible” and Stage 2 “Concept Verified”	Responses to comments will be included in the Final Post Access report and be publicly available.
Post Access Report	The final post-access report will be submitted to MHK-DR and be publicly available.

7.5.2 Data Processing

The acquired data has been analyzed by Calwave to guarantee that it is in a correct form. In addition, the testing results have been compared with the numerical predictions to make sure that the data collected are desired data. Data obtained from ABS in the form of comments on documentation will be reviewed in detail and compared with existing analysis, with an identified action or response for each comment.

7.5.3 Data Analysis

Data provided to ABS for review includes multiple years of analytical and numerical modeling by different approaches:

- Frequency domain analytical modeling with two-port PTO modeling approach for PTO co-design (MATLAB); results led to current device sizing and PTO design characteristics.
- Higher-order dynamics modeling (up to 2nd-order dynamics) using python - PyDY multibody dynamics toolbox for assessment of parametric resonance conditions.
- WECsim time domain analysis (nonlinear BEM hydrodynamics, implementation of transfer functions from previous wave tank tests to represent experimentally derived hydrodynamics) used for irregular wave resource performance assessment, nonlinear controller tuning (approximation of causal impedance matching), failure mode assessment (e.g., PTO tether failure)
- Star-CCM+ modeling for viscous effects (as a function of the Reynolds and the KC number) and for 50-year return wave survival cases; staged failure modes.
- OrcaFlex umbilical and mooring modeling for design of umbilical connection point and floater configuration.

8 PROJECT OUTCOMES (REQUIRED FOR POST ACCESS REPORT ONLY)

8.1 RESULTS

Technical comments from ABS were created against the results as well as the responses to the comments from Calwave. The comments are summarized in the

8.2 LESSON LEARNED AND TEST PLAN DEVIATION

There are several lessons learned in this review process, a summarized listing is outlined below.

1. We can improve and over communicate time management, submittal items scheduling, comments response time and general review period schedule with Calwave.
2. Improve on documentation submittal schedule and schedule time of invoice payment

8.3 PATH TO CERTIFICATION

As shown in Figure 1 a five-stage process is followed that aligns with the typical product development phases of a new technology:

1. Feasibility Stage
2. Concept Verification Stage
3. Prototype Validation Stage
4. System Integration Stage
5. Operational Stage

ABS completed the New Technology Qualification process of the first two stages. CalWave will build upon the lessons learned and discussions concluded under this award and progress towards the Prototype Validation/certification stage with ABS for the PacWave device that CalWave currently plans.

Throughout the design process, CalWave will ensure that documentation aligns with requirements from ABS such that certification activities can be streamlined along the way. Guidelines such as the NREL risk management framework are helpful tools that will be used to structure the risk management work and summarize risk mitigation efforts for ABS.

The third stage of the NTQ process is the Prototype Validation Stage. The main objective in this stage is to validate with a prototype what was verified in the Concept Verification Stage. The following qualification activities along with future activities for the System Integration Stage should be highlighted in the New Technology Qualification Plan (NTQP) and submitted to ABS for review:

Engineering Evaluation

i) Systems Requirements and Description Document (SRDD)

- Review engineering documents that describe the component requirements and the interaction between components, subsystems, and the overall system if applicable.
- Detailed design documents including detailed drawings, product specifications, process and instrument details, detailed calculations, etc.
- Prototype test plans, test data (as requested), and test results summarized in a report.
- Additional qualification testing, data, and results identified in the design risk assessment

(e.g., FMECA).

ii) Inspection Test Plan (ITP)

iii) Detailed manufacturing plan.

Risk Assessment

i) The final updated risk assessment reports from the Concept Verification Stage (as applicable).

ii) The final design risk assessment (e.g., FMECA) report.

iii) The process risk assessment (e.g., process FMECA) report (as applicable).

iv) The final system Reliability Availability and Maintainability (RAM) analysis report (as applicable).

v) Final hazard register with all action items closed out.

ABS Survey

Survey during the manufacturing process and prototype testing may be required. The local ABS Survey office should be contacted ahead of time to arrange for any witness testing. Refer to Section 5/ 3.1.4 of ABS Guidance Notes on Qualifying New Technologies for additional information.

After prototype certification CalWave will target a type certification via ABS.

9 CONCLUSIONS AND RECOMMENDATIONS

The submitted document reviewed were aligned with ABS Guidance Notes for Qualifying New technologies and provided the technical comments are addressed satisfactorily, the appropriate statement of maturity levels will be issued.

Currently, two (2) maturity levels have been reached and the statements are being issued:

1. Feasibility Stage
2. Concept Verification Stage

CalWave will continue the work with ABS towards Prototype Certification in ABS's NTQ process and build upon the discussions and lessons learned from this project.

10 REFERENCES

The listed references from ABS Guidance Notes on Qualifying New Technologies were used in the review.

[1] ABS Guidance Notes on Qualifying New Technologies

[2] ABS Guide for Position Mooring Systems

[3] ABS Guidance Notes on Safehull Finite Element Analysis of Hull Structures

11 ACKNOWLEDGEMENTS

ABS gratefully acknowledges the financial support of TEAMER's Technical Support program (Round 3).

12 APPENDIX

A document with technical questions derived by ABS and CalWave's responses is appended to the end of this report. Furthermore, he Statement of Maturity letters and ABS Review response letter are included in the appendix of this report as part of the TEAMER deliverable:

STATEMENT OF MATURITY

Client Name: Calwave Power Technology
Date Issued: November 1, 2022

Certificate Number: T2313430

TECHNOLOGY FEASIBLE

This is to certify that

XWAVE WAVE ENERGY CONVERTER TECHNOLOGY

has been reviewed in accordance with the ABS *Guidance Notes on Qualifying New Technologies* [1]. The proposed technology concept is considered feasible with respect to its intended functions in accordance with the defined performance requirements as outlined in the Preliminary Design Report, Deliverable. The technology may proceed to the ***Concept Verification Stage***.

Description and Application:

CalWave is developing a wave energy converter (WEC) called xWave, which operates fully submerged and is classified as a submerged pressure differential type. As ocean waves pass over the submerged wave buoy, a pressure differential is created, exciting the absorber in multiple degrees of freedom to oscillate in resonance with the ocean waves. Energy is efficiently extracted using multiple independently controllable power take-off (PTO) units. Based on CalWave's 2 body WEC technology tested in the US DOE's Wave Energy Prize, multiple improvements on absorber geometry and PTO controls have been achieved.

Boundaries: N/A

Scope of Review:

1. Design basis, functional specification, and technical specification of the Xwave system.
2. System and function architecture details, such as functional flow block diagram if any.
3. Design details such as basic engineering drawings and engineering principles associated with further development.
4. Software tool- review of validation test data (as requested), and test results
5. Design analysis methodology and any available preliminary results, e.g. hydrodynamic analysis, device dynamics and kinematics modeling, PTO modeling, electrical system modeling and umbilical modeling.
6. Details regarding physical and functional interface requirements (mechanical, electrical, software, etc.).
7. Applicable design references, codes, standards and guidelines, and technical justification for any proposed deviations.
8. Risk assessment study developed by Calwave

Comments/Notes: Refer to ABS review response letter dated 1 November 2022.

Reference Documents:
[1] ABS *Guidance Notes on Qualifying New Technologies*

ABS shall in no event be held liable for any identified/unidentified hazardous scenarios or qualification activities associated with this technology.

Approved By: Jin Wang

Jin Wang
Director, ABS Corporate Technology

STATEMENT OF MATURITY

Client Name: Calwave Power Technology
Date Issued: November 1, 2022

Certificate Number: T2313430

CONCEPT VERIFIED

This is to certify that

XWAVE WAVE ENERGY CONVERTER TECHNOLOGY

has been reviewed in accordance with the ABS *Guidance Notes on Qualifying New Technologies* [1]. The proposed technology concept is verified as being capable of performing its intended functions in accordance with the defined performance requirements as outlined in the Preliminary Design Report, Deliverable. The technology may proceed to the ***Prototype Validation Stage***.

Description and Application:

CalWave is developing a wave energy converter (WEC) called xWave, which operates fully submerged and is classified as a submerged pressure differential type. As ocean waves pass over the submerged wave buoy, a pressure differential is created, exciting the absorber in multiple degrees of freedom to oscillate in resonance with the ocean waves. Energy is efficiently extracted using multiple independently controllable power take-off (PTO) units. Based on CalWave's 2 body WEC technology tested in the US DOE's Wave Energy Prize, multiple improvements on absorber geometry and PTO controls have been achieved.

Boundaries: Additional requirements in ABS review response letter dated 1 November 2022 applies.

Scope of Review:

1. Review documents that describe the concept verification design requirements.
2. Review design documents that include but not limited to the configuration, drawings, analytical models, etc.
3. Review preliminary manufacturing plan, initial test plan and test results.
4. Review testing in PacWave and PacIsland. Verify if the XWave system at a conceptual level satisfies the specified functional and performance requirements. The performance requirements are to be established by Calwave and should be detailed enough that the technology can be evaluated against the expected performance criteria.
5. Review updated risk assessments from the feasibility stage and preliminary design risk assessment (e.g., FMECA) report.

Comments/Notes: Refer to ABS review response letter dated 1 November 2022.

Reference Documents:
[1] ABS *Guidance Notes on Qualifying New Technologies*

ABS shall in no event be held liable for any identified/unidentified hazardous scenarios or qualification activities associated with this technology.

Approved By: Jin Wang

Jin Wang
Director, ABS Corporate Technology

Task – T2313430
PDDS PID: 4749947 Technology Feasible & Concept Verification
New Technology Qualification of CalWave's wave energy converter (WEC)
Comments response

Attention: Mr. Dan Petcovic <dan@calwave.energy>, Calwave Power Technology (WCN: 473530)

The documents shown in the drawing list below are reviewed in accordance with the applicable requirements of the following:

- ABS Guidance Notes on Qualifying New Technologies

We have also received responses to our comments created and sent in our e-mail dated 17th June 2022, 4th August 2022, and August 31st, 2022 and advise as follows:

- Comments E-001, E-003, E-006 through E-008, S-001 through S-016 have been resolved and closed.
- Comments E-002, E-004, E-005, E-009, E-010 remain open pending more details to be provided in the next phase of the design.

Please refer to the list of comments provided below and associated with this review to be resolved.

Electronic copy of the documents, appropriately stamped, are available in the ABS Client Portal.

For any clarifications, contact Jude Tomdio at 281-877-6016 or jtomdio@eagle.org.

Very truly yours,

Jin Wang

Jin Wang
Director, ABS Corporate Technology

Drawing List

Submitter:	CALWAVE POWER TECHNOLOGIES, INC. (473530)	
Drawing No	**Revision No**	**Drawing Title**
DE-EE0008951	2	Preliminary Design Report, D1.9 (CalWave Design for PacWave)
ABS Review Comments & Adjudication	0	ABS Review Comments & Adjudication

Thread No	Comment Text	Facilities	Action
E-001	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 3.4: What would be the voltage limitations found out by the simulation approach?		
Calwave Response	The voltage limitation was set at 5% voltage drop, per IEC60364-5-52 table G.52.1.		
	Noted. Comment resolved.		
E-002	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 3.4: What were the parameters/ values used for the modelling of the electrical system during the simulation approach, including cable connection, transformers, converters, inverters, supercapacitors, etc.?		
Calwave Response	Motor control is based on a torque reference for each load step and the export inverter controls the DC bus voltage and reactive power on the AC grid side (assumed as an infinite grid). Brake resistor and supercapacitors are controlled via DC bus voltage.		
	We note your response, however the intent of this comment was to clarify the values/ratings of the electrical equipment/component used during the simulation. E.g. transformers, converters, inverters, supercapacitors, etc. what values/ratings were assigned to these equipment/component during the simulation? In this regard, this comment remains open. Please advise.		
Calwave Response	The more detailed component selection is on-going in the electrical model.		
	Comment remains open pending detailed component selection in next phase of the design.		
E-003	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 3.3: Was there any control loop strategy used during the PTO modeling , which one, can this be provided?		
Calwave Response	PTO torque setpoints are tracked Additionally, a torque estimator based on speed, direction, displacement, and (hydraulic) pressure is used.		
	Noted. Comment resolved.		
E-004	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 3.4: What are the voltage and frequency ride through bands of the modelled generator when integrated with the grid, and under terminal fault conditions?		
Calwave Response	We have not yet completed this in the electrical model.		
	We understand the voltage and frequency ride through bands have not yet been completed in the electrical model, therefore, this comment remains open.		
Calwave Response	Pending results of on-going work.		

	Comment remains open pending the next phase of the design.		
E-005	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 3.4: we understand that a more advance model will be developed, in this regard we await: short circuit or bus fault condition study during the modeling process, what is the short circuit current capability of the generator unit?		
Calwave Response	Inverter has HW short circuit trip at 2,700A, 2micro-sec reaction time.		
	We note your response and understand that a more advanced electrical model will be created, this comment remains open pending the advanced electrical model and your submission of the short circuit study or bus fault condition study.		
Calwave Response	Pending results of on-going work.		
	Comment remains open pending the next phase of the design.		
E-006	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4: What would be the protection philosophy for reverse power protection during "wave-to wave" power flow fluctuations		
Calwave Response	Reverse power is intended during some portions of the wave cycle, the electric machines are designed for full four quadrant control.		
	Noted. Comment resolved.		
E-007	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4: What would be the protection philosophy for reverse power protection during "wave-to wave" power flow fluctuations?		
Calwave Response	Reverse power is intended during some portions of the wave cycle, the electric machines are designed for full four quadrant control.		
	Noted. Comment resolved. (Duplicate comment created in error).		
E-008	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4: what would be the mitigating techniques in the case of the power quality issues?		
Calwave Response	Shore side conditioning equipment is envisioned, such as pf correction - to be determined based on electrical model.		
	Noted. Comment resolved.		
E-009	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4: what would be the power management and ESS management system architecture, how they will be integrated, and how they will meet/ interact with any control requirement from the grid?		
Calwave	We are currently working with NREL on a more advanced model and grid integration study.		

Response			
	We note that you're currently working with NREL on a more advanced model and grid study, we advise that this comment remains open till the details of the integration of the power management and ESS management system architecture and how they interact with any control requirement from the grid is known.		
Calwave Response	Pending results of on-going work.		
	Comment remains open pending the next phase of the design.		
E-010	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	What would be the protection control strategy for isolating the generator unit from any fault condition (external and internal seen from unit's terminals) so that the unit was not damaged?		
Calwave Response	The intent is to included relays/reclosers upstream of the inverters; the specifications of the circuit protection hardware is pending completion of the more advanced electrical model		
	We understand that generator protection will be provided after completion of more advanced electrical model, this comment remains open pending the advanced electrical model. Please note that details of the generator protection is to be submitted during the review of the advanced electrical model.		
Calwave Response	Pending results of on-going work.		
	Comment remains open pending the next phase of the design.		
S-001	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 3.2 DEVICE DYNAMICS & KINEMATICS MODELING Results of the absorber body velocity obtained from experiments with the numerical models were compared. Only two motions (surge and heave) are provided. How about other motions (pitch, yaw) comparison.		
Calwave Response	Heave and surge are shown because they are the most energy contributing motions. Energy is also gained through all other degrees of freedom, however due to the relatively small contribution, they are less considered in device modelling and kinematics modelling. Furthermore, Heave, Surge and Pitch resemble a joint set of kinematic constraints. While there will be uncertainty stacked from Heave and Surge motion, the Pitch motion has to match to ultimately lead to the same Heave and Surge motion.		
	Noted. Suggest to add a few sentences in the report for clarification. Comment can be closed once added.		
Calwave Response	Section 3.2 updated in the report to include suggested information.		
	Comment closed.		
S-002	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 3.5 UMBILICAL MODELING		

	In Table 3, only one wave direction is considered. Is this the worst condition for the umbilical?		
Calwave Response	Yes, because the primary concern is the umbilical coming into contact with mooring lines due to lateral motion; so it was modelled with a wave direction 90 degrees to the connection point.		
	Noted. Comment closed.		
S-003	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 3.5 UMBILICAL MODELING: The peak tension [redacted] is small compared to the allowable tension via the umbilical specifications. What is the allowable tension and the reference rule/guide?		
Calwave Response	Umbilical was significantly oversized for strain due to risk of inadvertent tensioning of cable during deployment, or in the event of a mooring failure. [redacted] was used as a maximum limit, as this was within the standard capability of the manufacturer.		
	Noted. Comment closed.		
S-004	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 3.5 UMBILICAL MODELING: Further work is needed relate to umbilical fatigue as well as larger bends in extreme wave events such as the 50-year return wave.		
Calwave Response	During larger sea states (e.g., 50-yr return wave), the WEC operates at a significantly lower submergence depth, which reduces the stroke & related umbilical motion to similar to the design case. Additionally, due to the increased depth, there is a larger bend radius in the dynamic umbilical. Agree that more work will be needed to assess fatigue.		
	Noted. Comment closed.		
S-005	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4. PRELIMINARY XWAVE SYSTEM OVERVIEW: Please describe how the depth control will be implemented during operation.		
Calwave Response	The WEC controller determines depth via hull pressure sensors and mooring line length input. Sea state is determined via an external wave data buoy (and supported by internal calculations based on mooring line stroke & forces). The depth controller then determines an appropriate depth based on a sea state based look up table and other variable setpoints in the controller.		
	Thanks for the details on the methodology of the controller. Is the depth of the X100 absorber body controlled by adjusting the lengths of the mooring lines? If so, can you describe how the mooring lines are adjusted during the operation, manually? Comment can be closed once explained.		
Calwave Response	Yes, the mooring lines are connected to a winch based rotary power train, the mooring line length is adjusted by winching in the line with the rotary PTO.		
	Comment closed.		

S-006	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4.1.1 Structural System Description: Are the strength and buckling check according to DNVGL-DT-119?		
Calwave Response	Yes.		
	Noted, comment closed.		
S-007	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4.1.1 Structural System Description, Pressure hull: It states that the peak stress (bending + tensile) imposed on the hull girder section, two cylindrical sections, is less than 40% of the allowable stress. What is the allowable stress and the reference Rule/Guide.		
Calwave Response	125 kPa (per Table 4), based on DNVGL-ST-119.		
	Noted, comment closed.		
S-008	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4.2 POWER TAKEOFF. Belt: In table 6, it states that the min cord SF to Break should be 2.5. What is the SF obtained for the belt from analysis. What is the reference Rule and Guide for the belt specifications?		
Calwave Response	IEC SF is 1.67 from 62600-10 (mooring standard). The 2.5 factor was a recommendation from the manufacturer (Nemos) who got it from references on wire rope. For this initial pilot, we decided to be more conservative and use the larger safety factor. For future systems, we plan to use the 1.67 IEC SF.		
	Thanks for the clarification on the safety factor criteria. What is the safety factor resulted from the load analysis.		
Calwave Response	1.67.		
	Comment closed.		
S-009	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4.2 POWER TAKEOFF. Belt: The report states that "We expect fleet angles to develop from the dynamics of our system and the resistive moments opposing fairlead motion including the restorative force of the length of twisted belt between fairlead and PTO, fairlead bearing and seal friction, and various inertial/gravitational effects." Are these considered in the belt analysis. Is twist going to be an issue?		
Calwave Response	Yes, these resistive moments are considered in the belt analysis and have been observed in the smaller scale deployment. In both cases, acceptable twist was observed. Additionally, the roller arm of the fairlead acts to translate excessive twist into torque that works to rotate the fairlead.		
	Can you add your response sentences to the report. Comment can be closed once added.		
Calwave	Section 4.2 updated in the report to include suggested information.		

Response			
	Comment closed.		
S-010	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4.2 POWER TAKEOFF. Fairlead: Any previous experience with such a fairlead design? Risk assessment?		
Calwave Response	Yes, a similar fairlead design (at smaller scale) was used for our current San Diego pilot system. Primary design input from risk assessment included 1. Belt providing sufficient torque to turn the slew bearing -> longer arm was included in between main fairlead body and roller pins 2. Potential for twist -> roller arm included that minimizes allowable twist and translates into torque 3. Biogrowth rubbing on belt -> observed in smaller scale deployment that moving parts self-clean of biogrowth, no noticed effect to belt.		
	Noted, comment closed.		
S-011	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4.4.2 Anchor Design Framework: It states that the maximum line tension is [redacted] kN here. But in Table 4, the maximum line tension listed as [redacted]0kN. Please explain.		
Calwave Response	Maximum line tension identified in section 4.4.2 does not include the 1.67 SF that is included in Table 4.		
	Thanks for the clarification. Is the maximum line tension of [redacted]alculated value from mooring analysis, and the [redacted] allowable line tension (usually called minimum breaking load)? If so, could you please clarify this in the report. Comment can be closed once clarified.		
Calwave Response	Section 4.4.2 updated in the report to include suggested information.		
	Comment closed.		
S-012	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4.4.2 Anchor Design Framework Minimum safety factor: what is the calculated mooring line safety factor.		
Calwave Response	1.67 (IEC 62600-10, Consequence class 1, table 3).		
	Noted, comment closed.		
S-013	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4.4.2 Anchor Design Framework Minimum line tension: please provide the reference Rule/Guide relate to this minimum line tension.		
Calwave Response	Minimum line tension is a control setpoint in order to prevent slack in the mooring lines, this is not from a Rule/Guide rather than a performance optimization parameter.		
	Noted, comment closed.		
S-014	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical

	Section 4.4.4 Mooring Line Design Framework Fatigue of the mooring line need to be considered for final design.		
Calwave Response	Concur, this was not consider for shorter duration deployments but will be in the final design. CalWave uses empirical and analytical models as well as experimental data obtained from belt bench testing to estimate fatigue safety.		
	Noted, comment closed.		
S-015	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 4.4.4 Mooring Line Design Framework Mooring line length: 90m, what is the corresponding submerged depth? It is anticipated that bottom chain will be used. Please provide the mooring line components: HMPE, length; Chain, length.		
Calwave Response	No bottom chain is planned, the full 90m is intended to be synthetic (HMPE). Submergence depth is variable between 1 [redacted] meter and adjusted using the PTO systems.		
	Noted, comment resolved.		
S-016	DE-EE0008951 - Preliminary Design Report, D1.9 (CalWave Design for PacWave)		Technical
	Section 5. X100 OPERATION AT PACWAVE AND PACISLAND: It states that the common PTO control including submergence depth and absorber geometry control as effective measures to increase performance and survivability of the X100. Please describe the procedures on control submergence depth.		
Calwave Response	Performance is increased by determining the optimal submergence depth for a given sea state, coupled with the optimal hatch opening (hull geometry); the optimal control setpoints are determined via kinematic modelling and confirmed with wave tank testing, dry PTO bench testing, and with results validated with recent scaled testing in San Diego. Survivability is increased with two methods. The first is submerging to greater depth during stronger sea states to avoid the forces occurring nearer the surface. Secondly, a load management hatch opens, reducing loads by allowing forces to pass through the center of the hull.		
	Thanks for the clarification. Comment closed.		

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

Final System Design with System Integration Plan

May 2019

CONTENTS

FIGURES

TABLES

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:

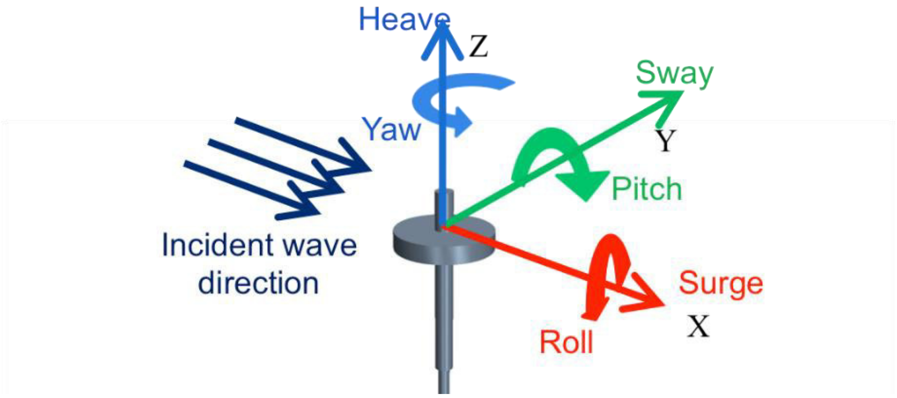


Figure 1: Global Coordinate System Position and Orientation used throughout this report. Picture / Scheme by WECSim - Theory section (https://wec-sim.github.io/WEC-Sim/theory.html)

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

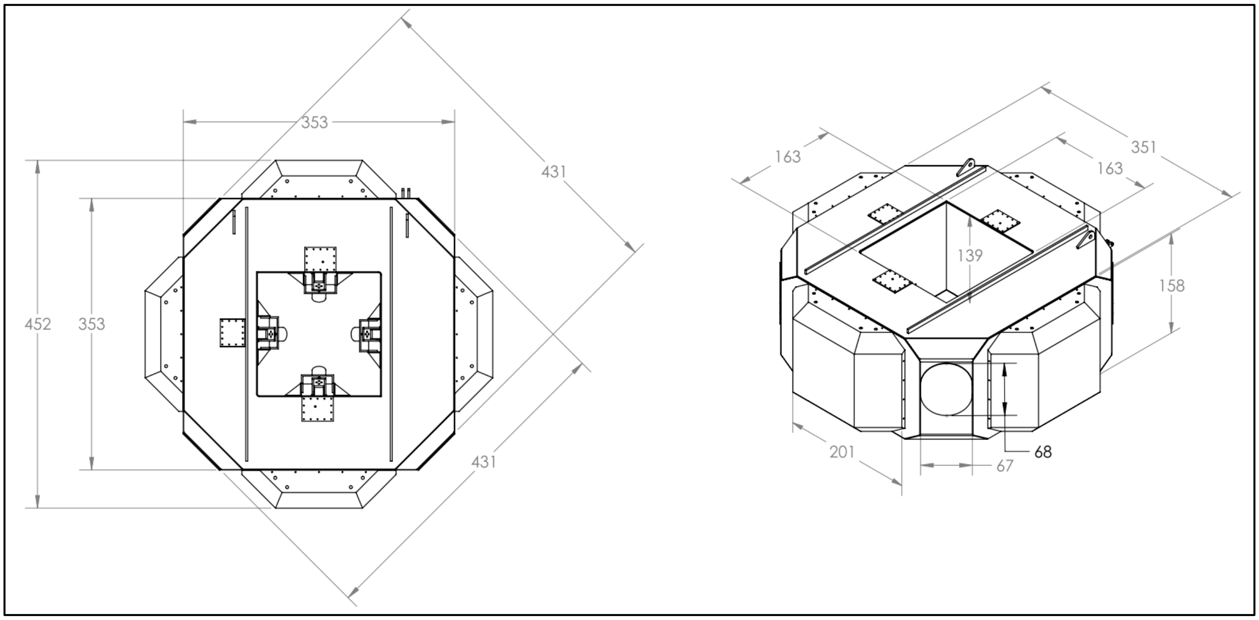


Figure 2: Hull layout general (dimensions in cm).

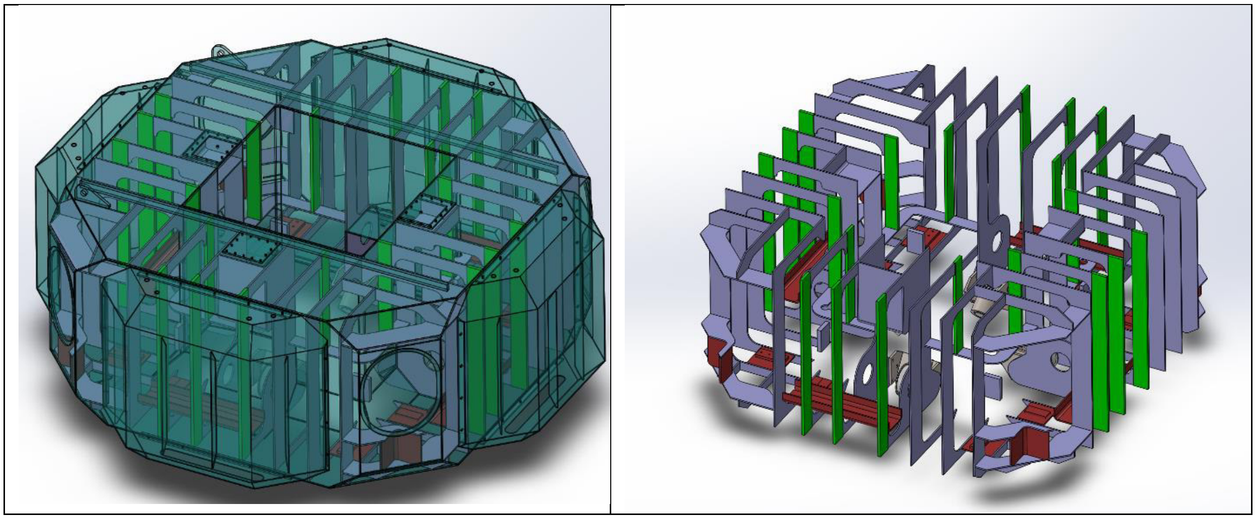


Figure 3: Hull shell and stiffener general layout.

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.

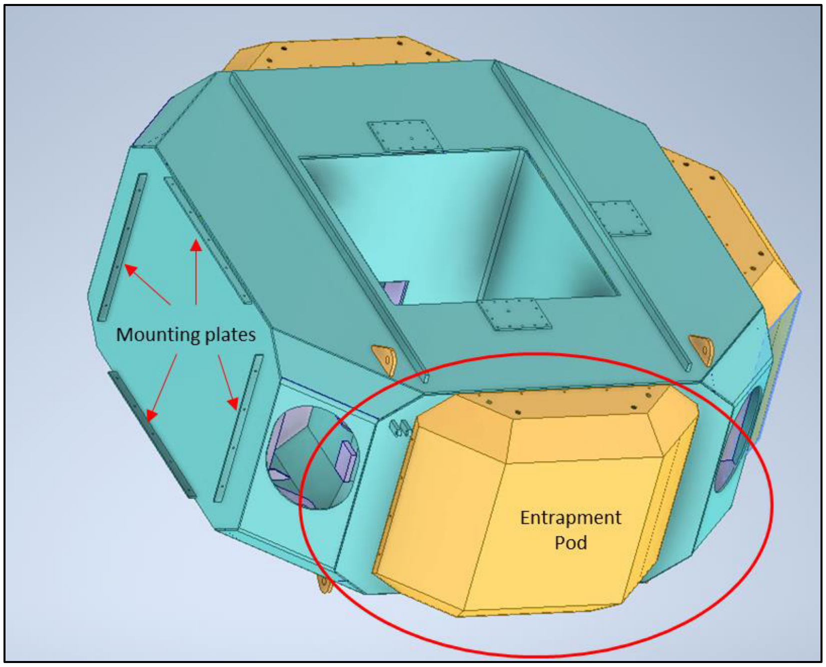


Figure 4: Water Entrapment Chamber.

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.

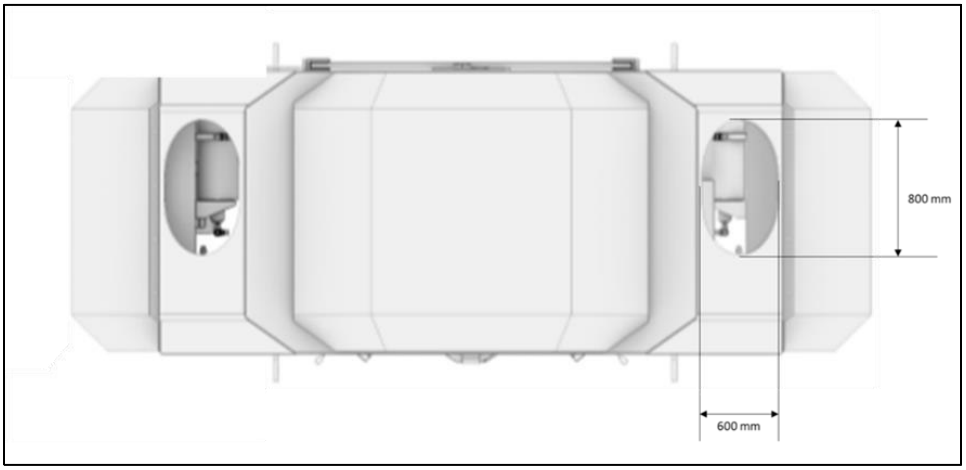
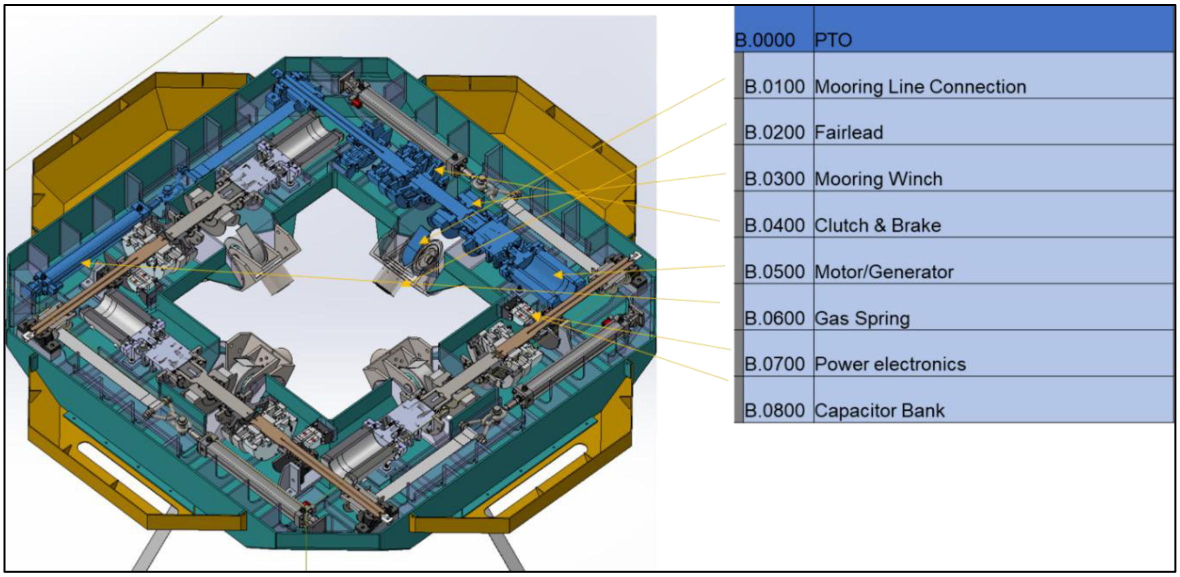


Figure 5: Access Hatch Dimensions.

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.

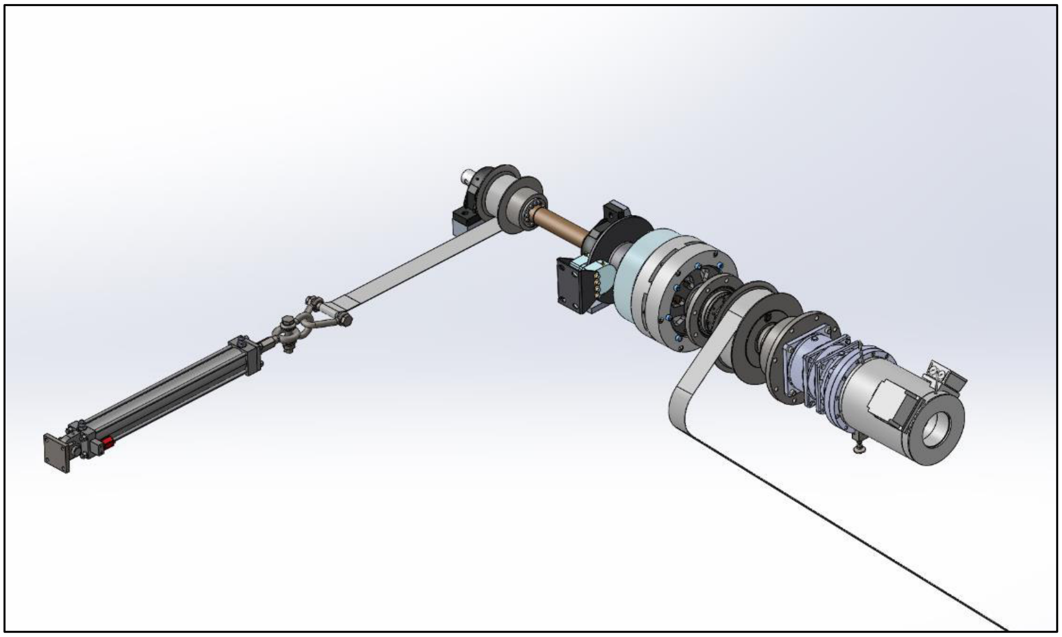
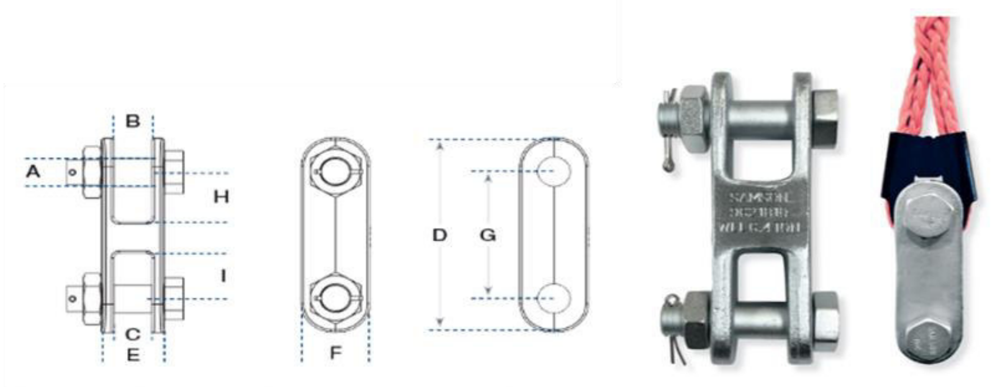


Figure 7: CAD drawing of individual PTO

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 WLL	Pin A	Top Gap Width B	Bottom Gap Width C	Overall Length D	Width E	Depth F	Pin Separation G	Top Gap Height H	Bottom Gap Height 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.

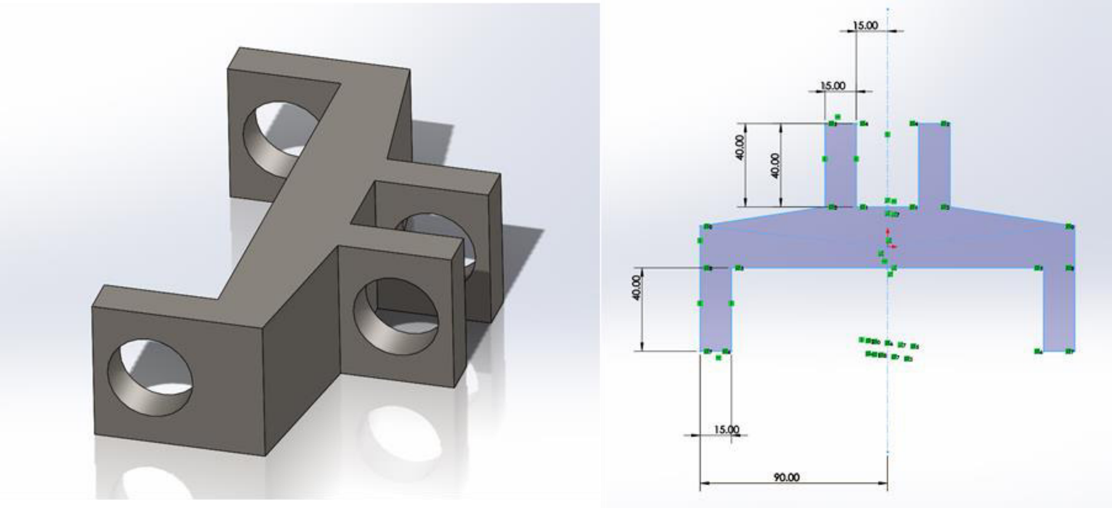


Figure 9: Modified H-link Adapter Design.

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.

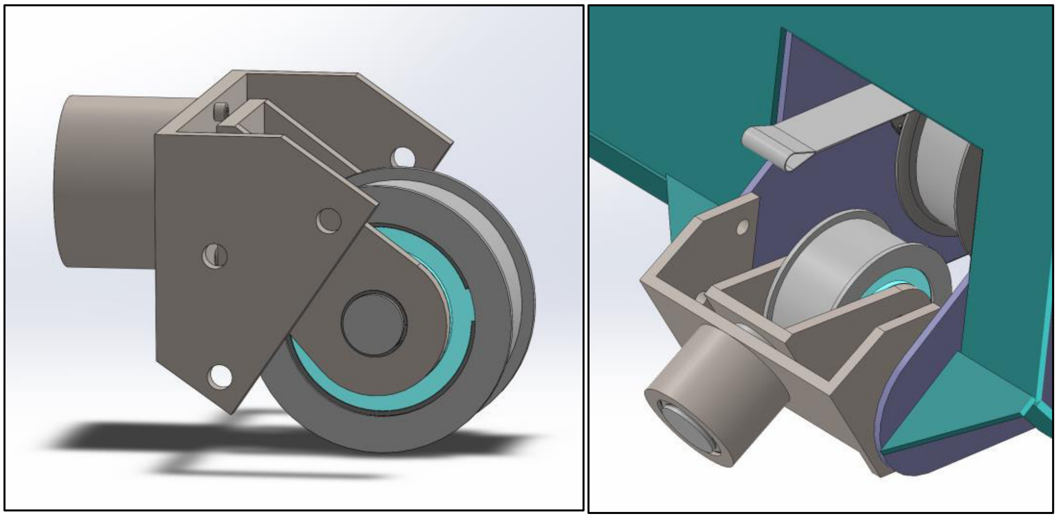


Figure 10: CAD of fairlead subcomponent (left) with close-up of hull integration (right).

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.

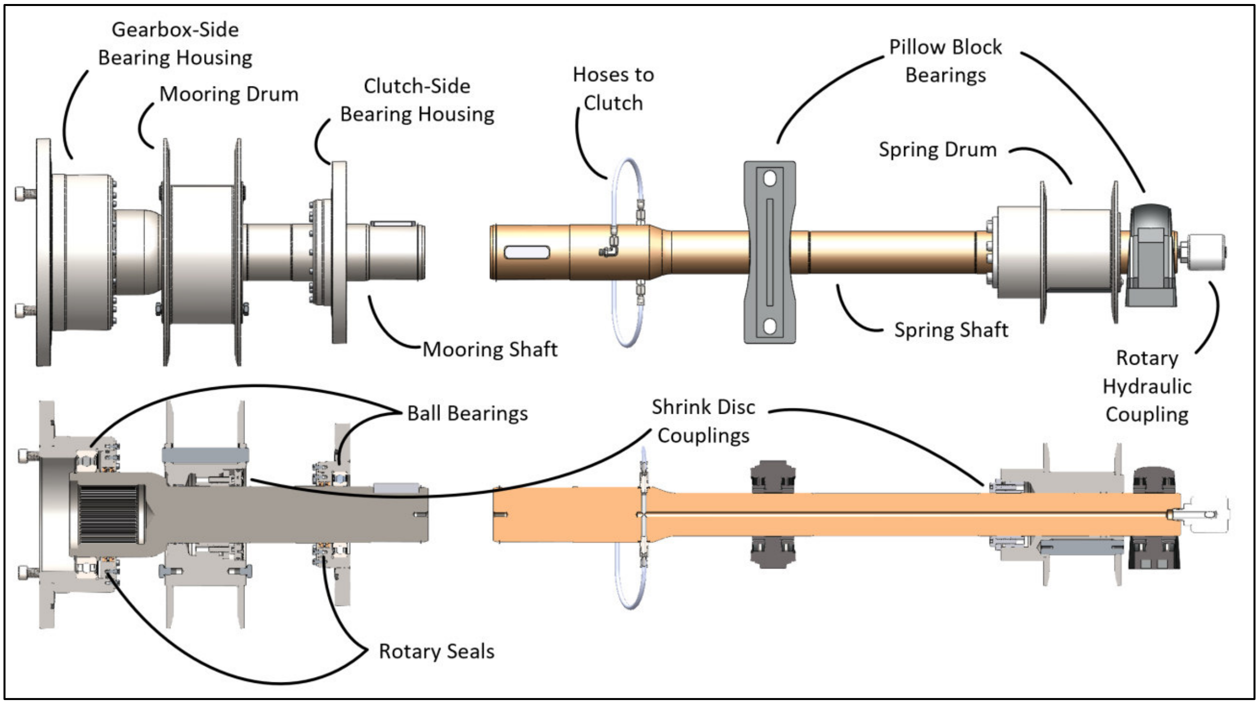


Figure 11: CAD rendering and cross section view of the mooring winch.

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.

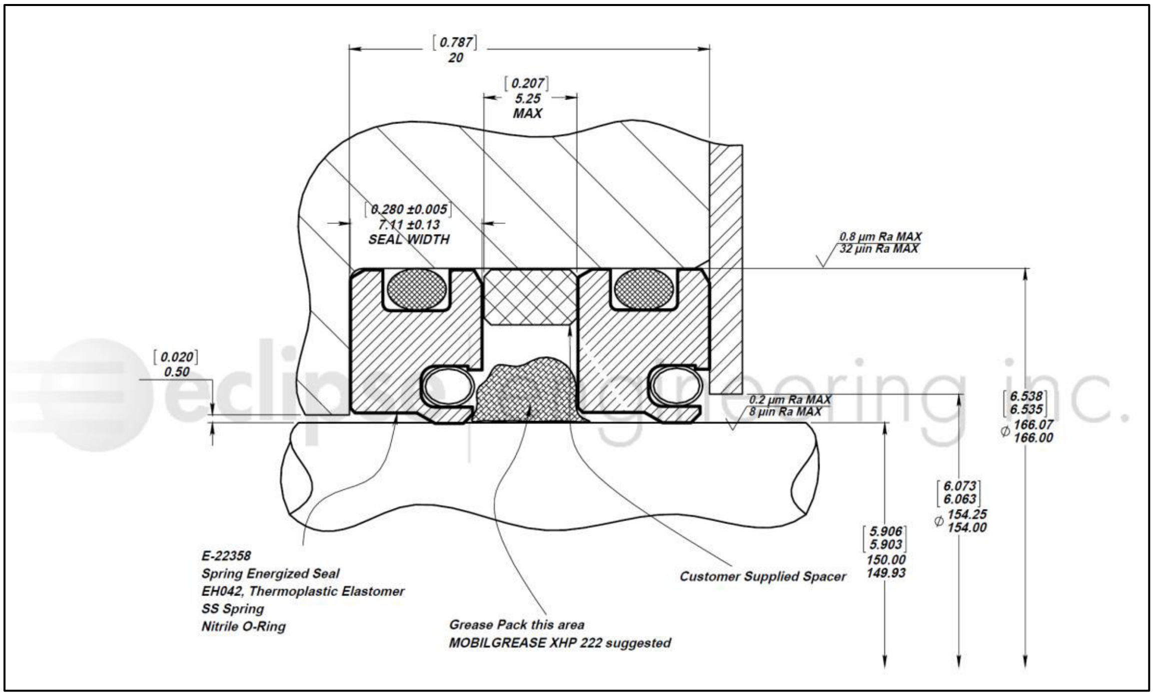


Figure 12: Cross sectional drawing of the dynamic rotary seal design on the gearbox side of the mooring drum shaft. Drawing provided by Eclipse Engineering Inc.

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.

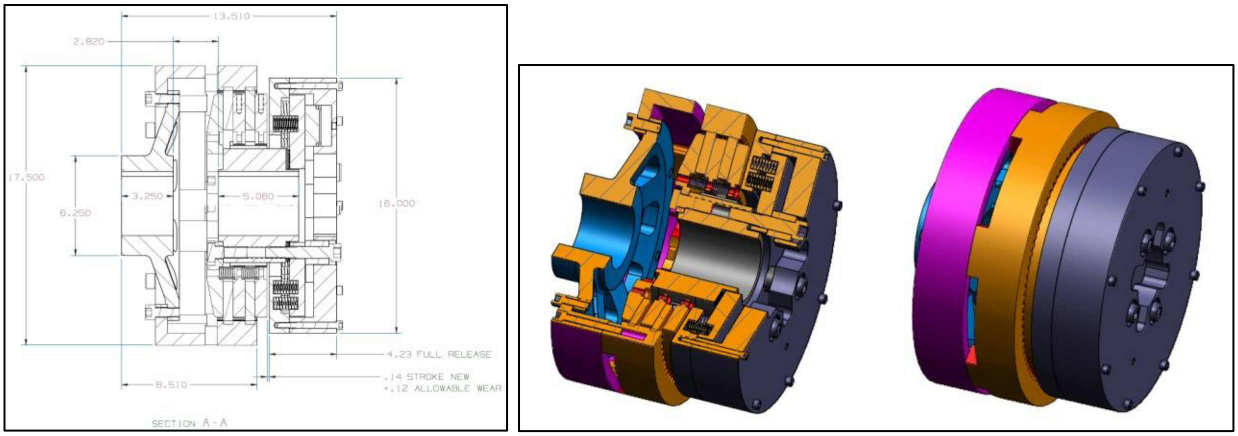


Figure 13: Clutch cutaway drawing (left) and CAD Isometric views (right). Note all dimensions are in inches. Provided by Wichita Clutch (Altra Industrial Motion).

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.

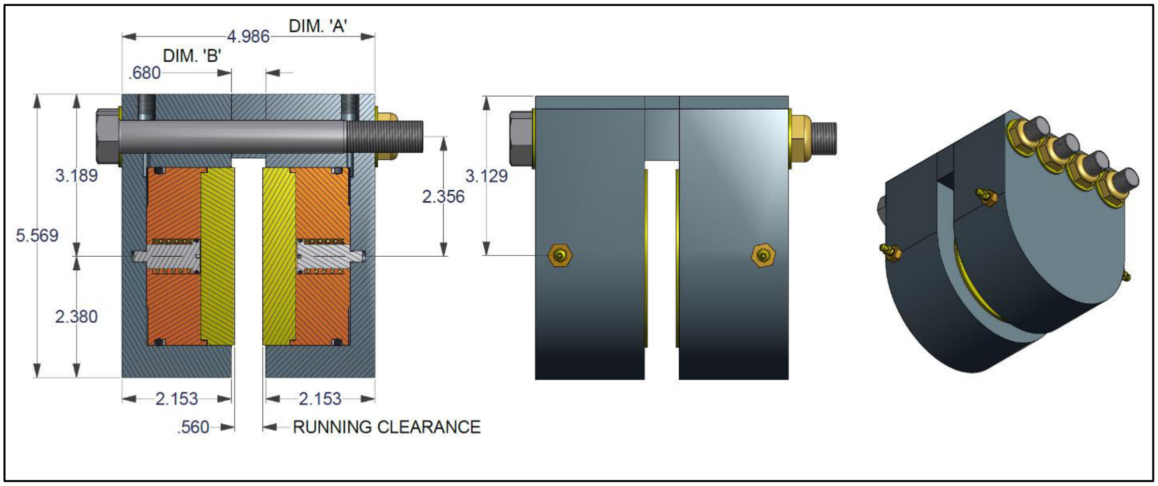


Figure 14: Drawing views including cutaway (left), top (middle), and isometric (right) of the caliper brake. Note all dimensions are in inches. Supplied by WC Branham.

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.

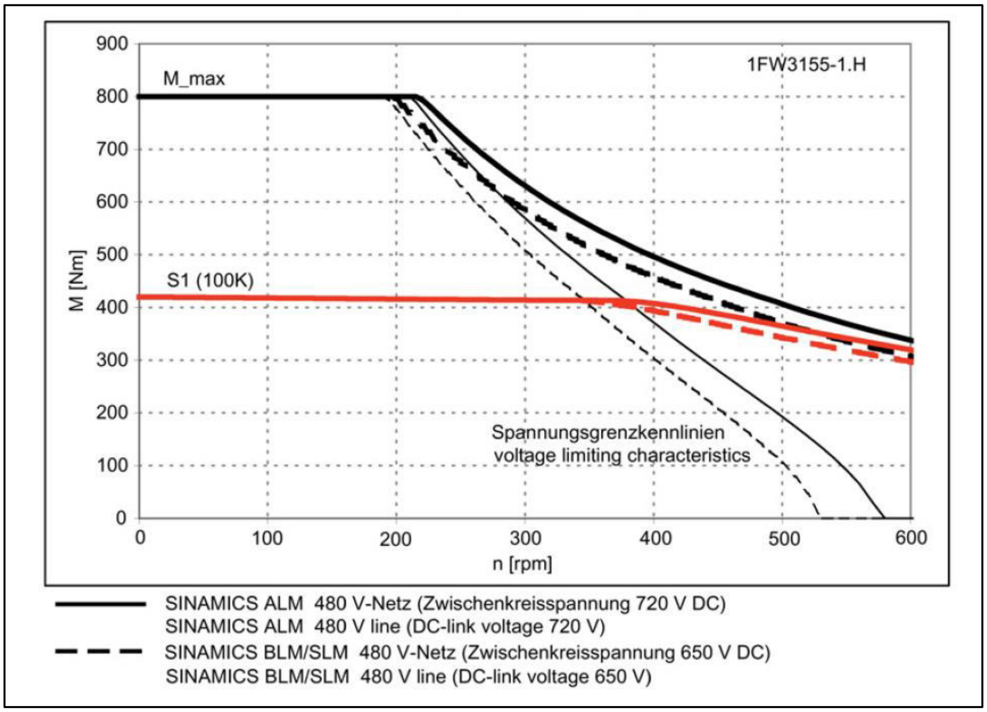


Figure 15: Speed/torque characteristic of the PMSM motor/generator.

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.

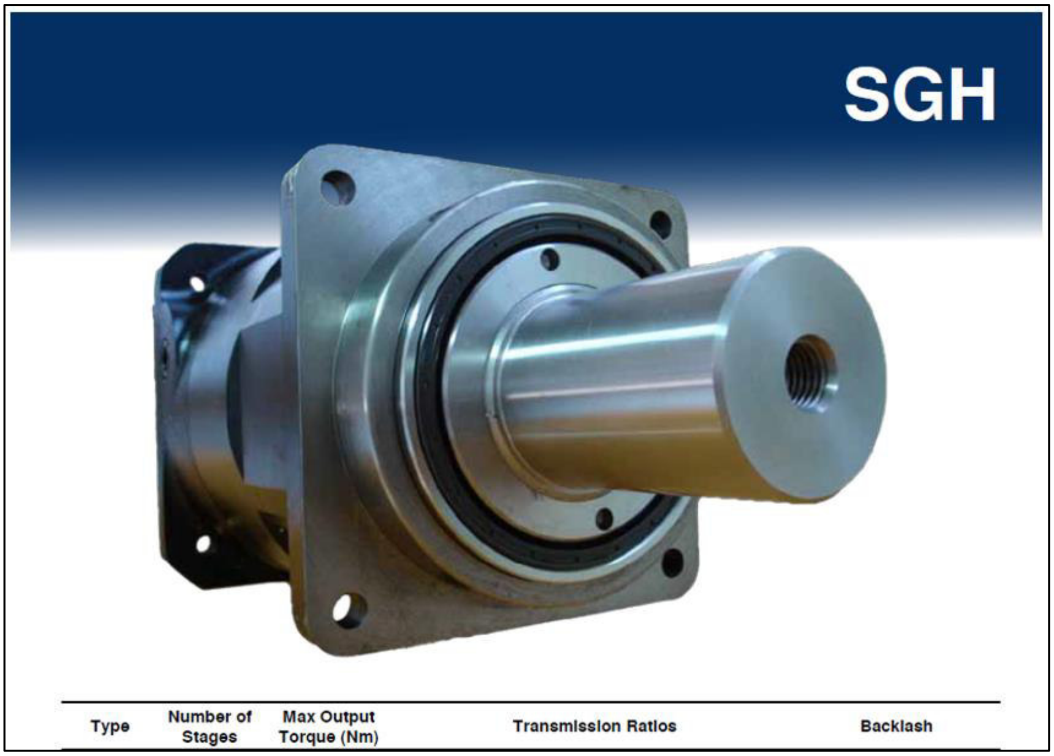
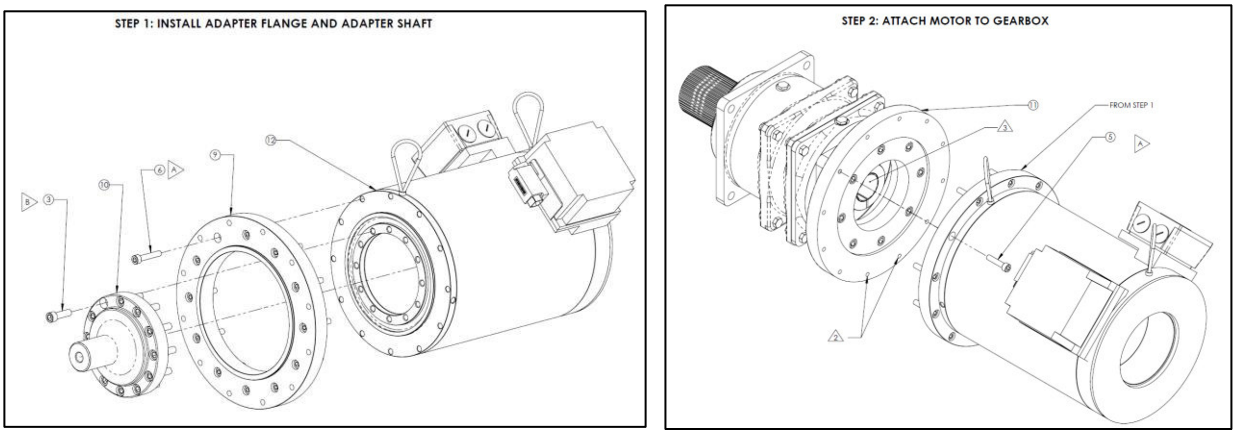


Figure 17: Servotak SGH-5000 Gearbox.



(a)

(b)

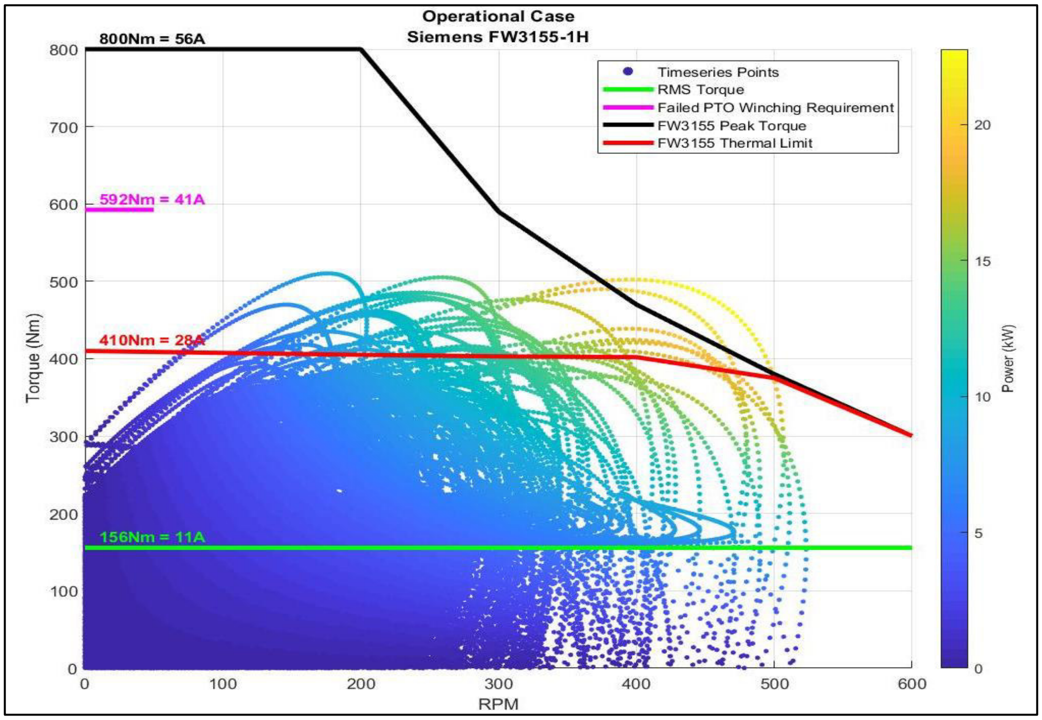
Figure 18: Motor and gearbox assembly. (a) Addition of custom shaft adapter; (b) Mounting of motor to gearbox.

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

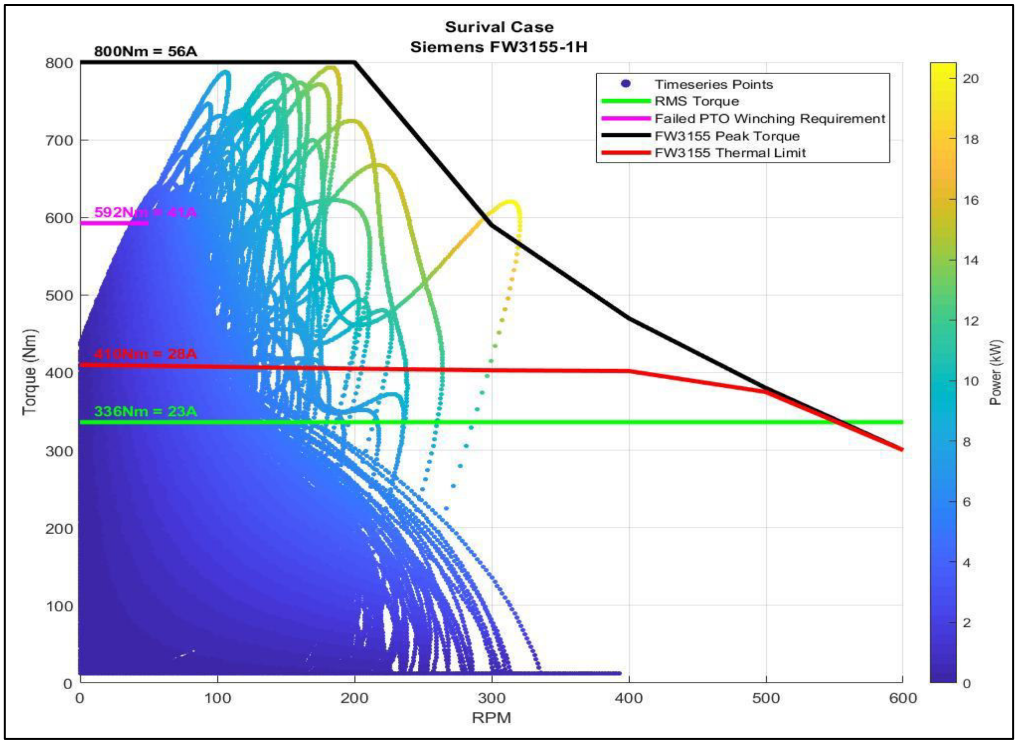
1. Normal Operations, in which the gas spring is acting on the drive shaft and the WEC is programmed to maximize energy capture.
2. Survival Mode, in which the gas spring is declutched the motor is responsible for PTO action to “de-tune” the WEC from large incoming waves.
3. Failed PTO Winching, in which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

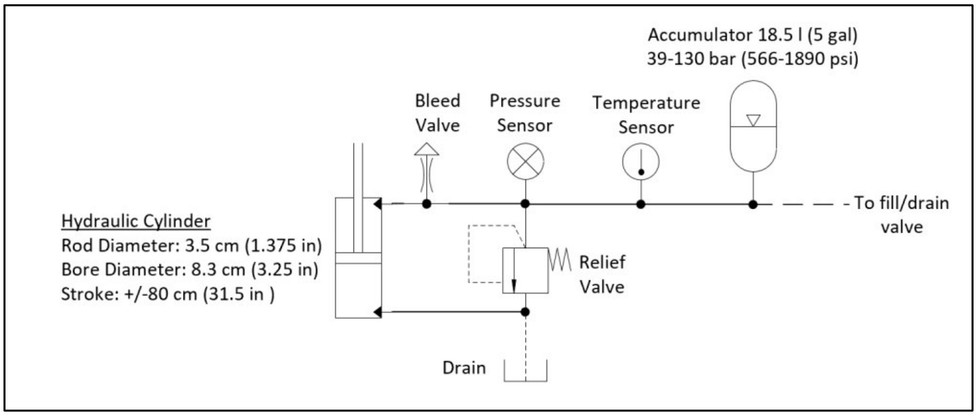


Figure 20: Schematic diagram of gas spring hydraulic circuit.

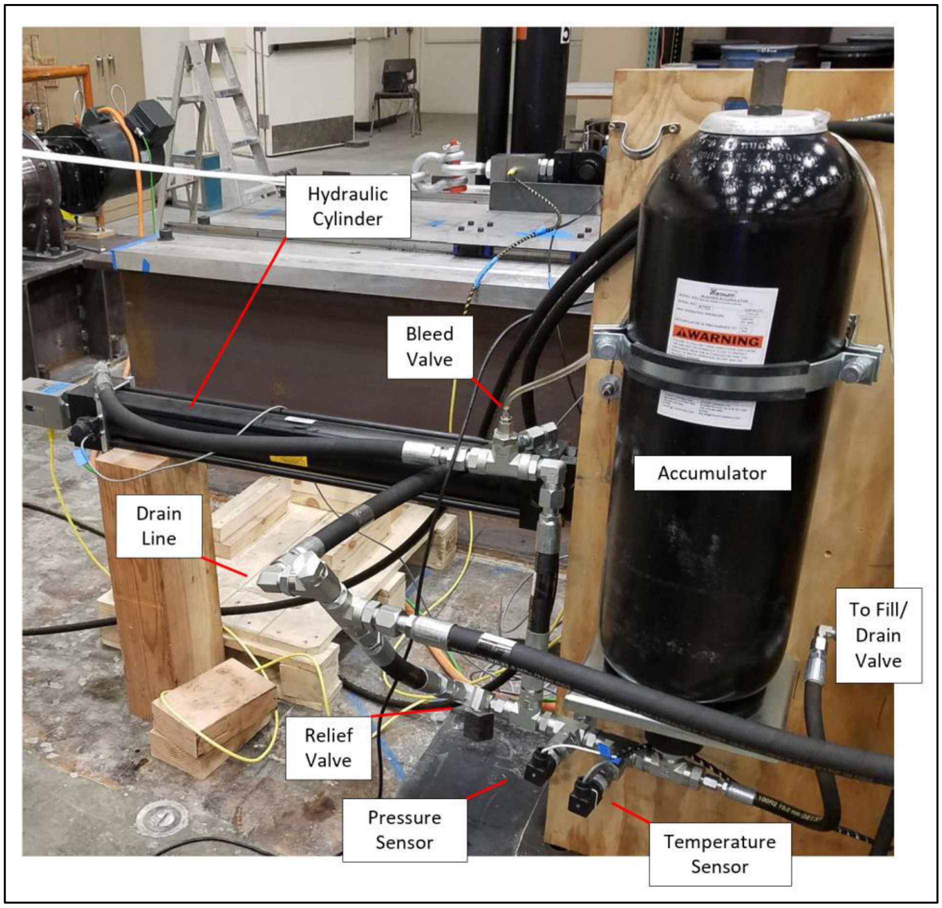


Figure 21: Picture of physical gas spring hydraulic circuit.

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.

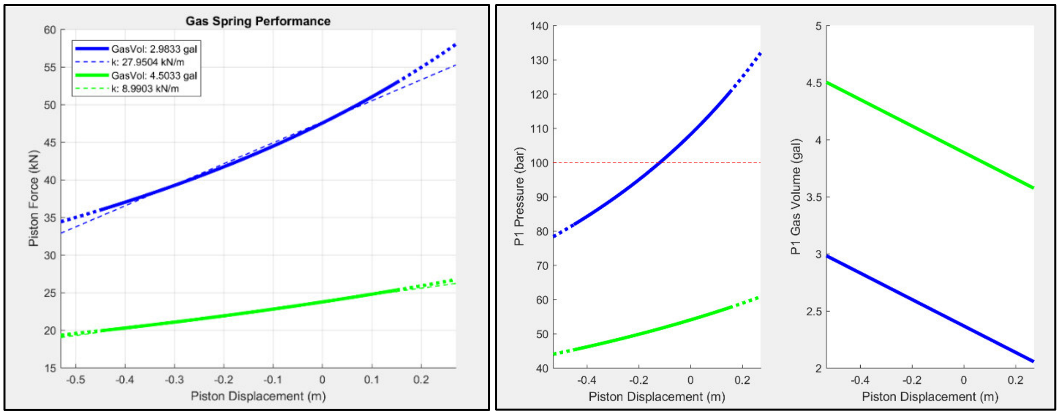


Figure 22: Analytical model results of gas spring characteristics during normal operation (green) and 3PTO survival case (blue).

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.

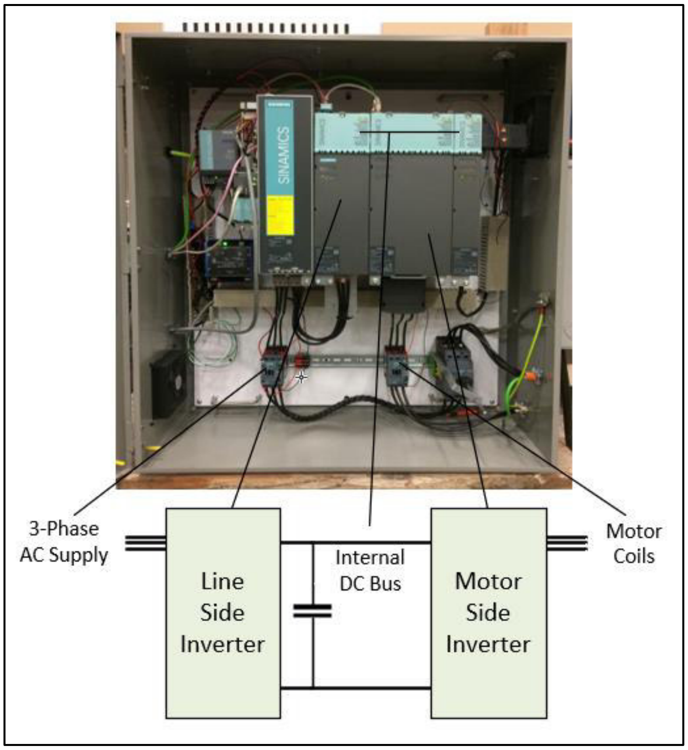
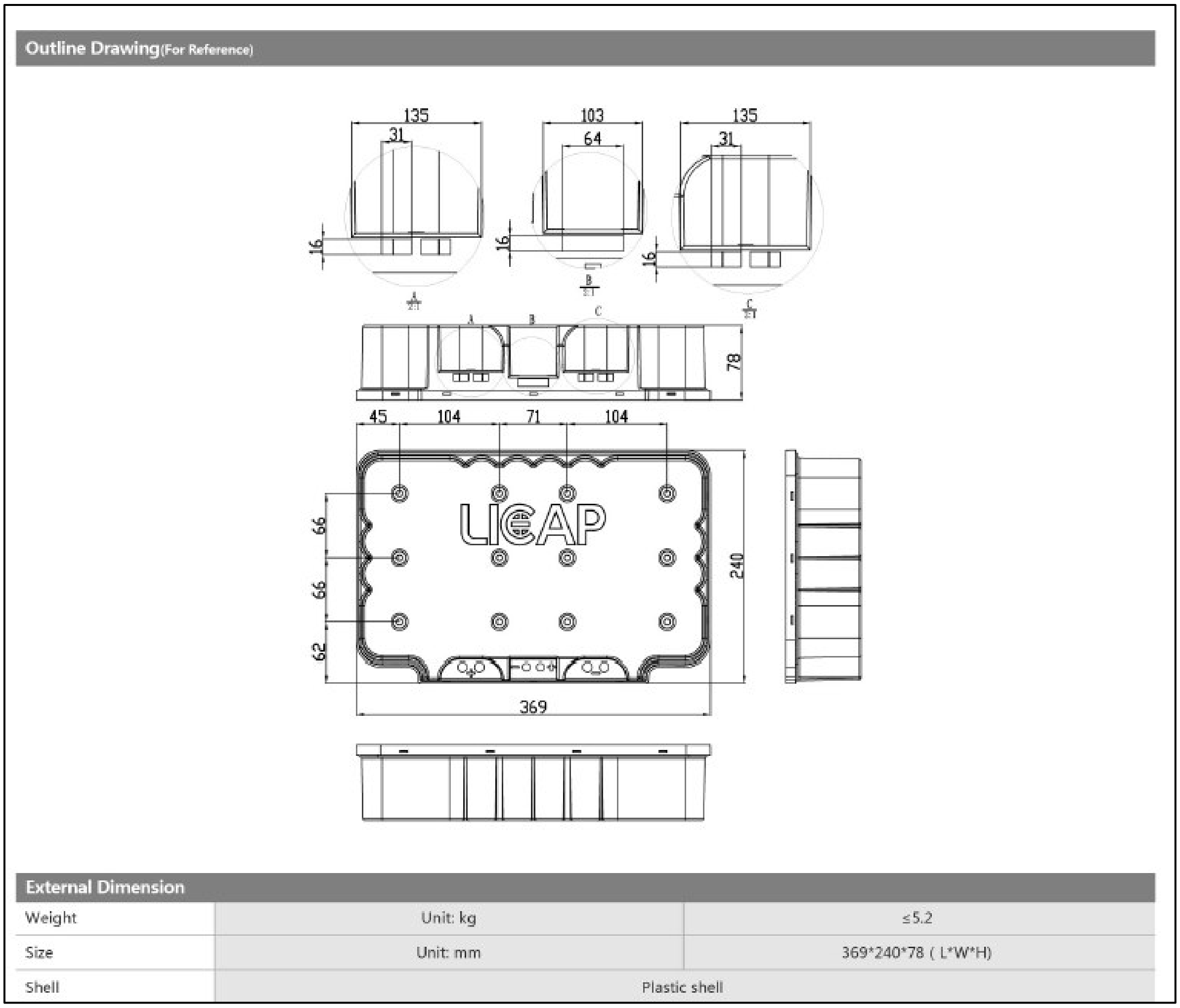


Figure 23: Siemens VFD lineup and corresponding generic back-to-back inverter topology.

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.

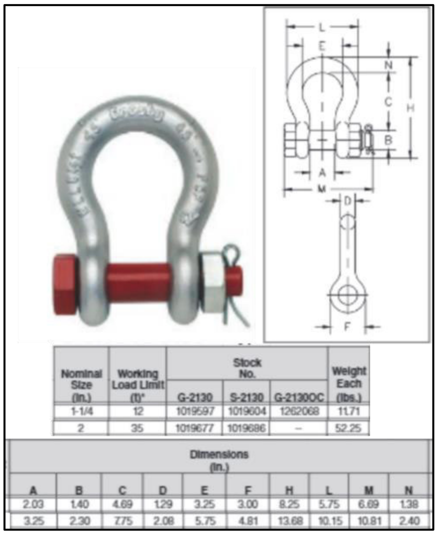
A schematic of our power electronics circuits is below. The DC link in the VFD will be broken out to an external bidirectional DC-DC buck-boost converter, which will interface the VFD's internal 650V DC bus with the external ultracapacitor bank. The topology works well in rudimentary simulations, and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

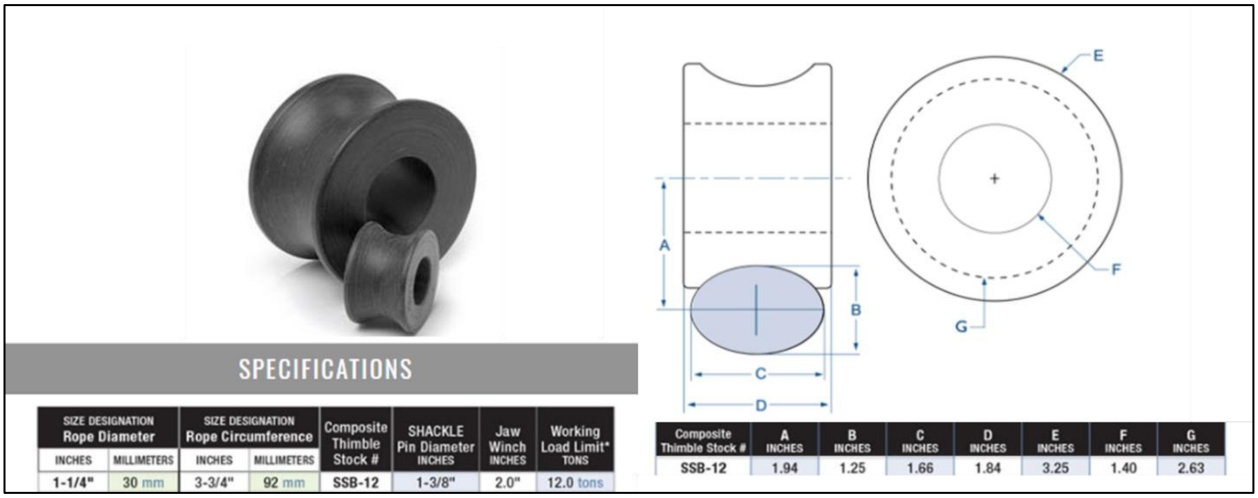
C.0200 Mooring Line

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;



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.

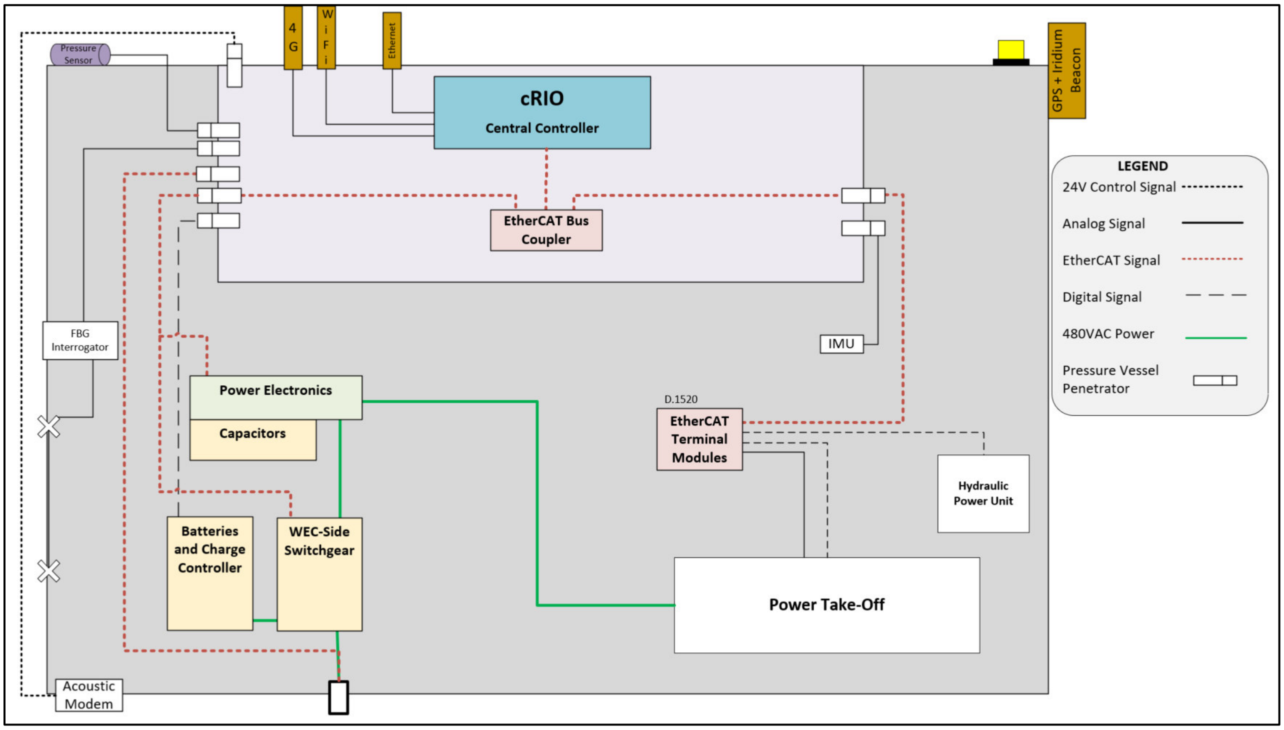


Figure 27: Simplified SCADA Layout.

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.

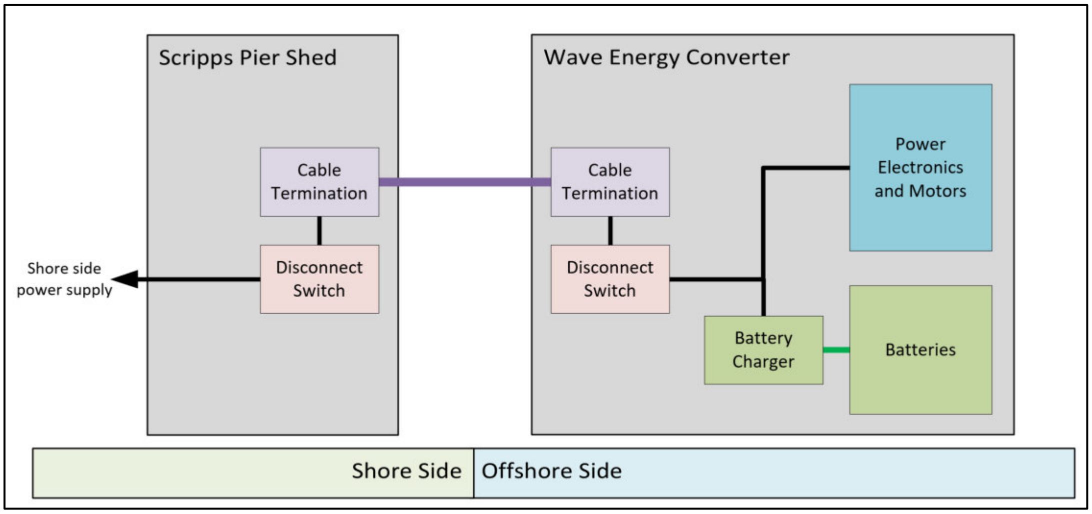


Figure 28: Schematic Overview of the WEC's electrical connection to the shore.

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.

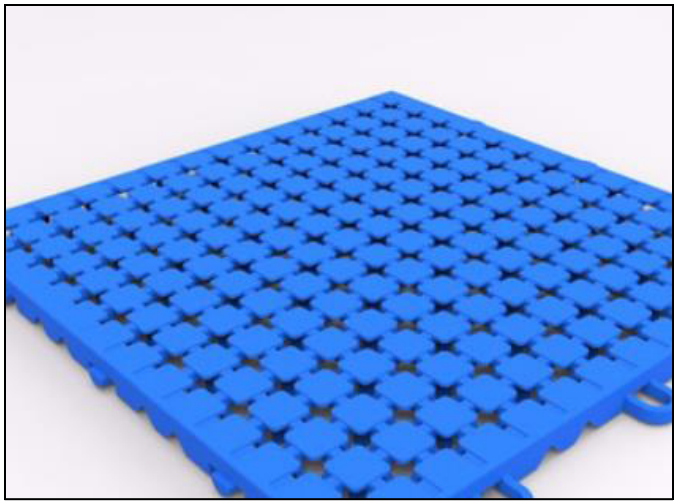


Figure 30 Example bilge grating.

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.

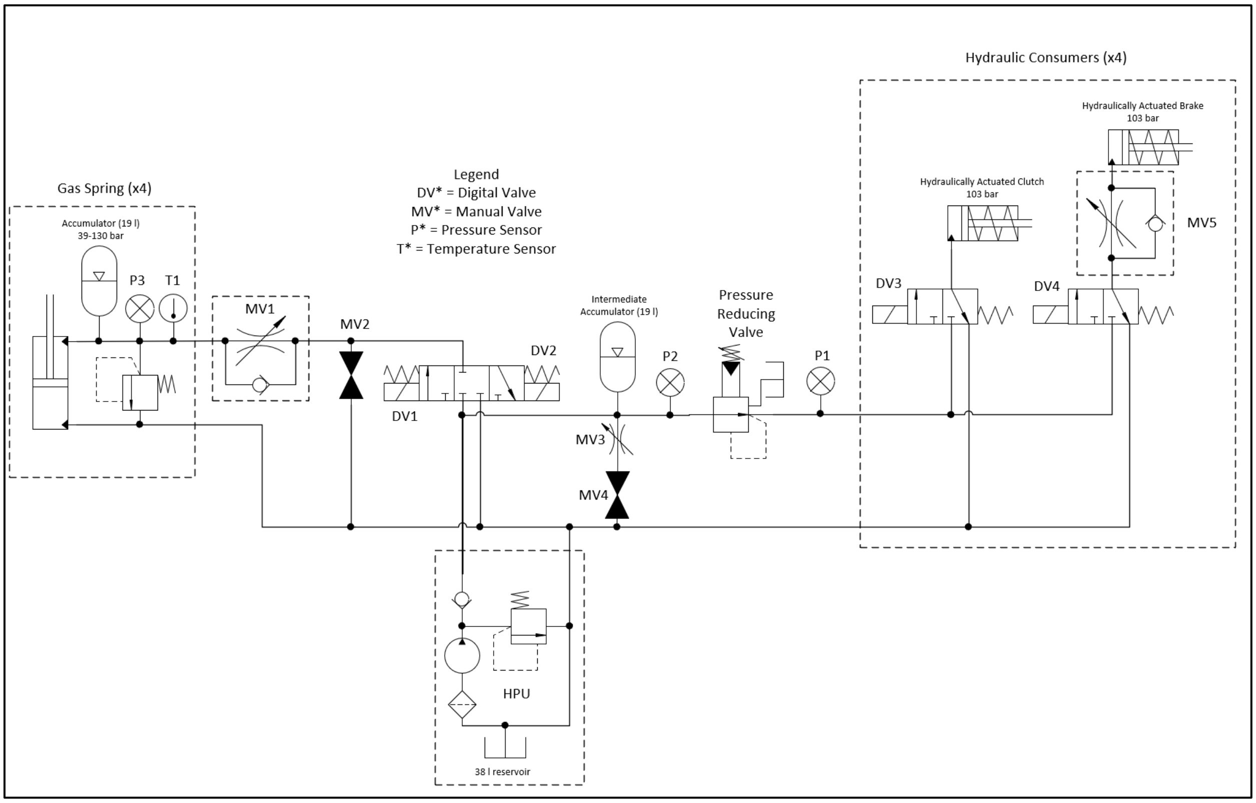


Figure 31: Hydraulic system circuit schematic.

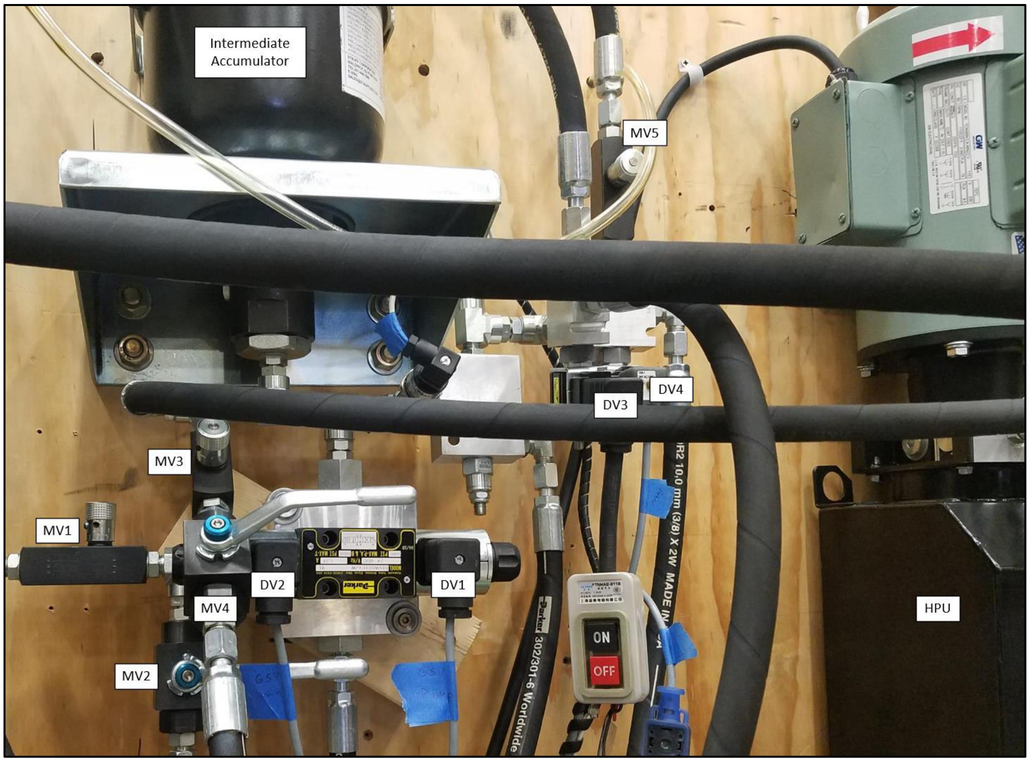


Figure 32: Preliminary hydraulic support system assembled to support PTO test stand.

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.

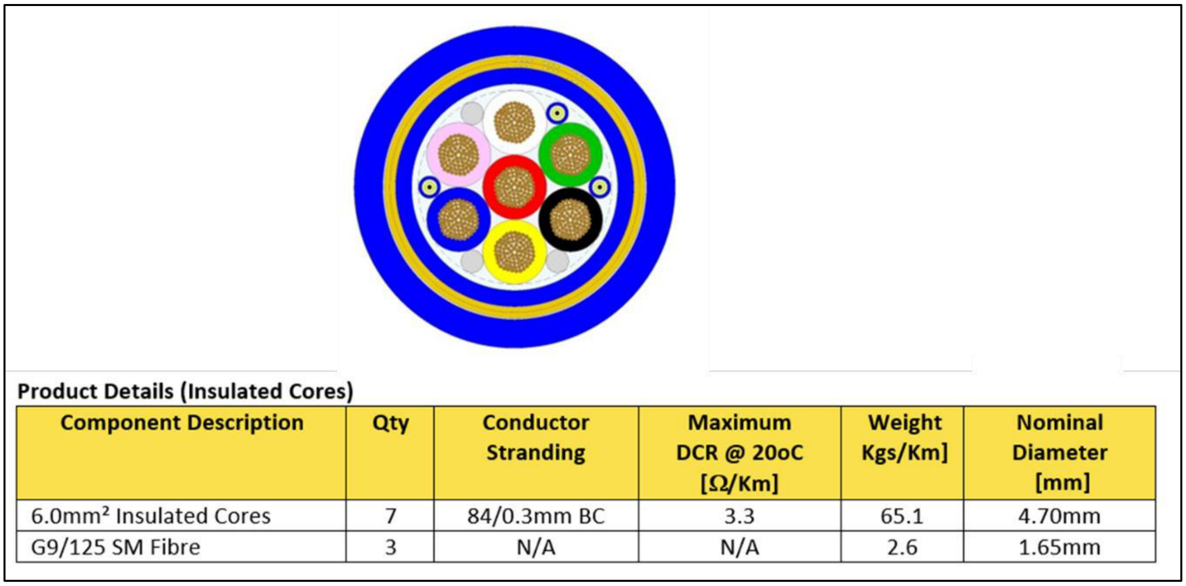
Table 5: Umbilical cable Physical Characteristics.

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.

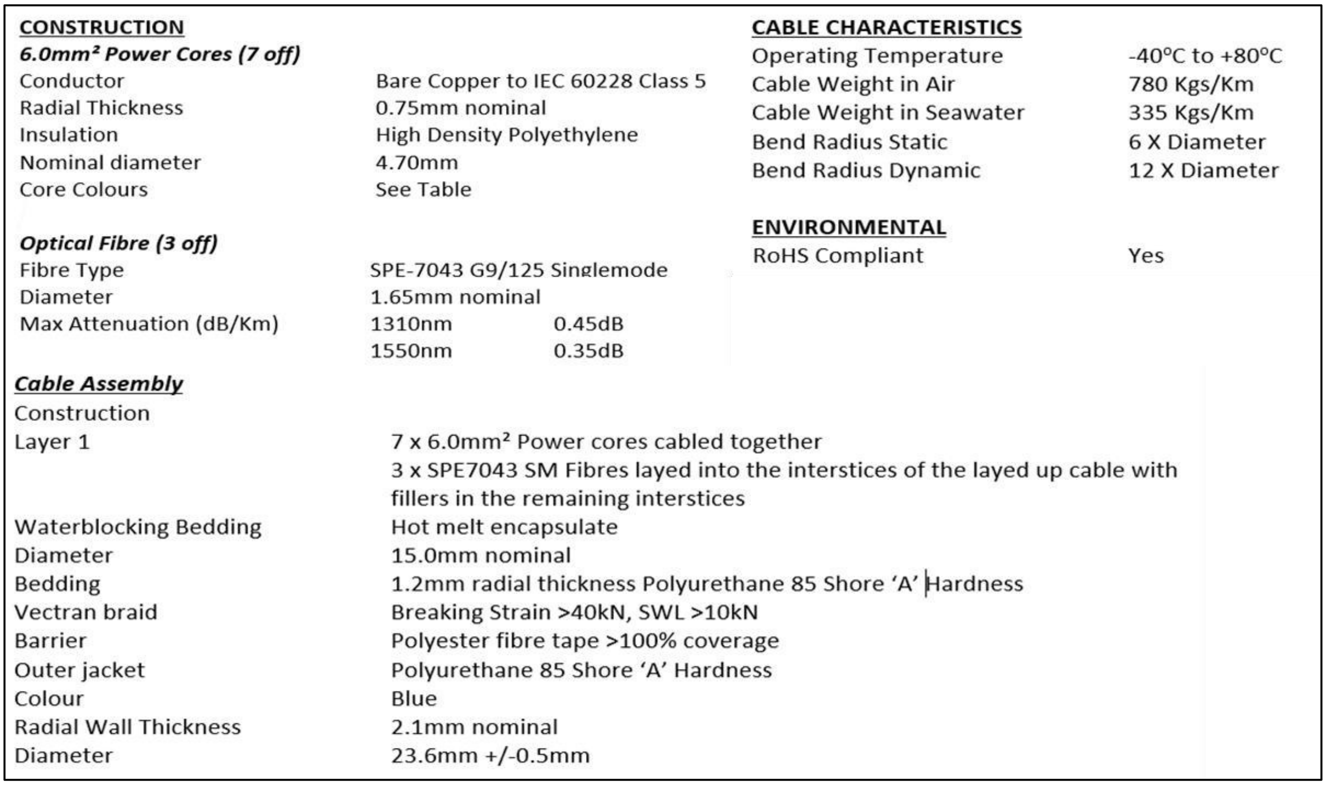
The selected umbilical cable is rated for 600V and consist of seven insulated power cores sized at $6mm^2$ (~10 AWG), three single-mode fiber optics, and Vectran braid strength member. Cable specifications are provided in the figures below;



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.

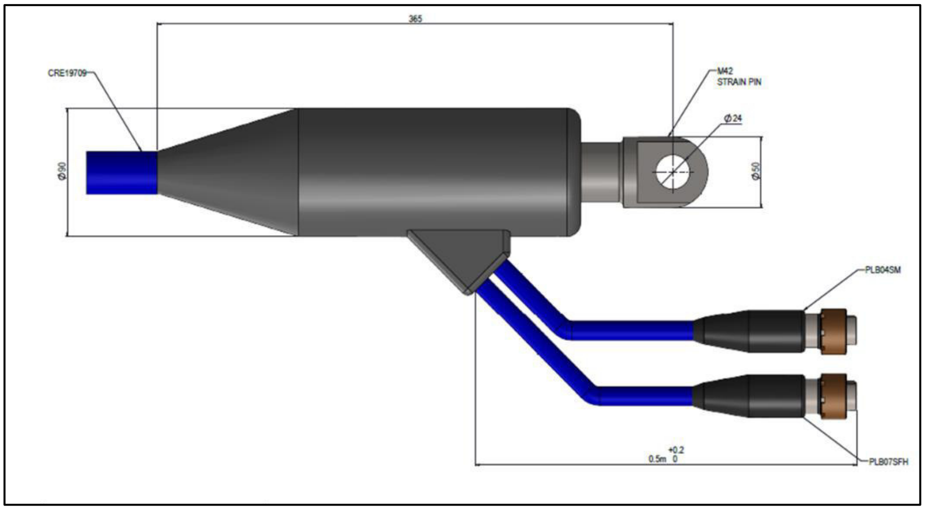
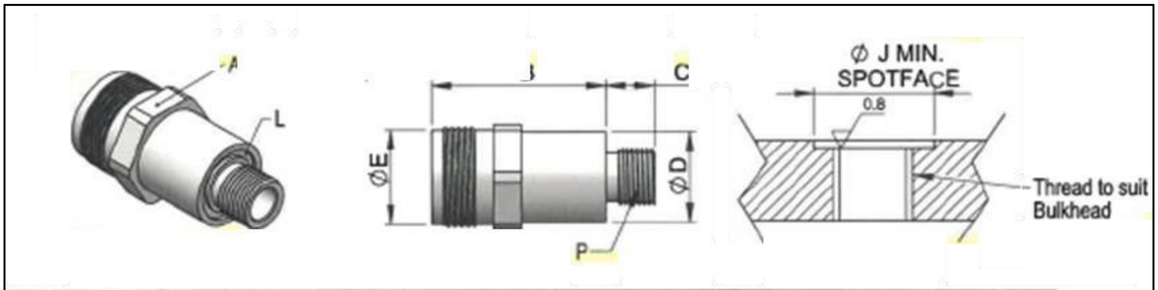
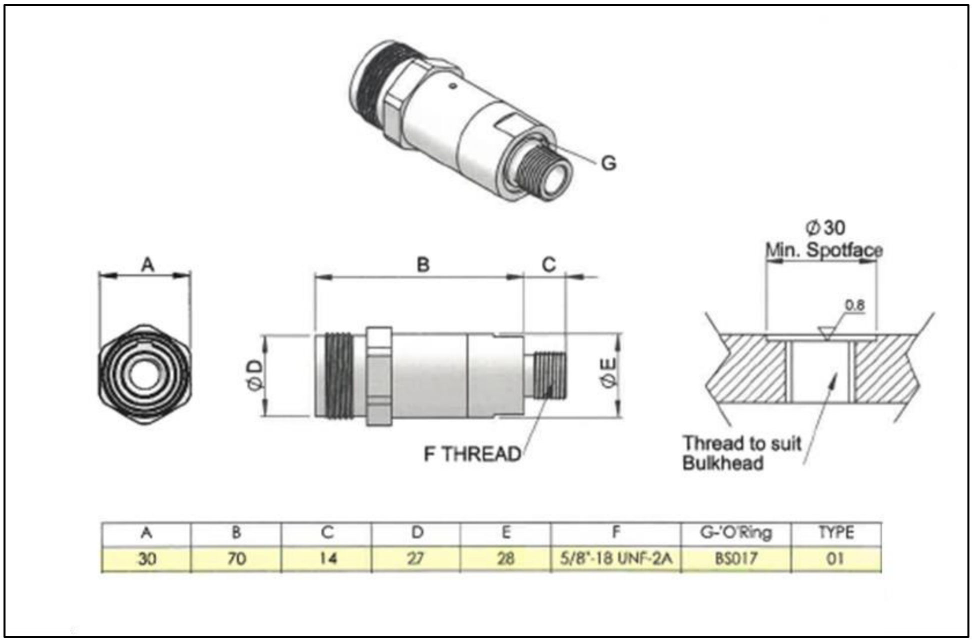


Figure 35: Umbilical Strain Termination w/ in-line connectors (dimensions in mm).



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.

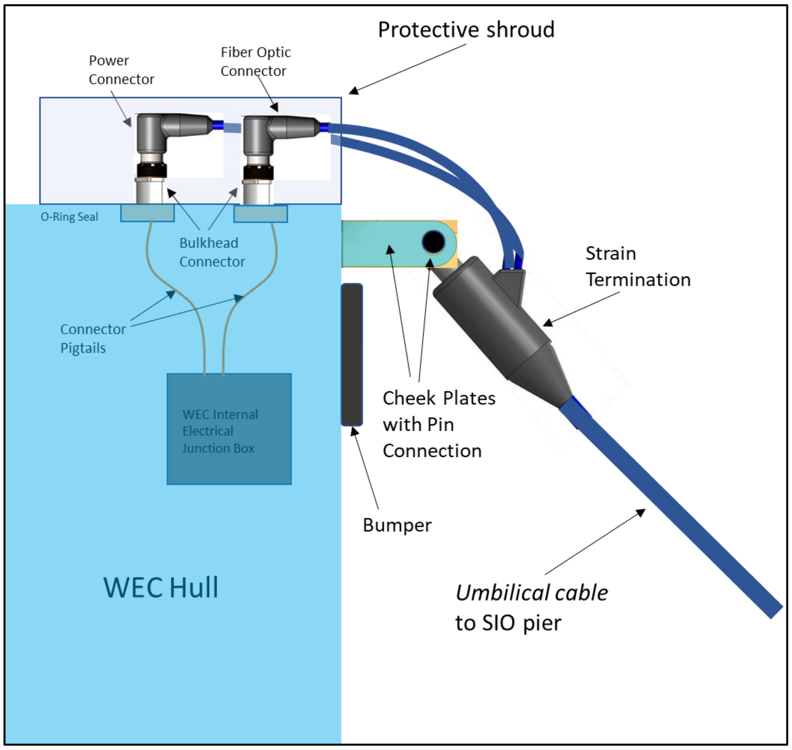


Figure 38: Umbilical Termination.

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.