Checkmate SeaEnergy Ltd.

User Project Enhanced Survivability Assessment of Anaconda Mk1C

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MaRINET2

ABOUT MARINET

The MaRINET2 project is the second iteration of the successful EU funded MaRINET Infrastructures Network, both of which are coordinated and managed by Irish research centre MaREI in University College Cork and avail of the Lir National Ocean Test Facilities.

MaRINET2 is a €10.5 million project which includes **39 organisations** representing some of the top offshore renewable energy testing facilities in Europe and globally. The project depends on strong international ties across Europe and draws on the expertise and participation of **13 countries**. Over 80 experts from these distinguished centres across Europe will be descending on Dublin for the launch and kick-off meeting on the 2nd of February.

The original MaRINET project has been described as a *"model of success that demonstrates what the EU can achieve in terms of collaboration and sharing knowledge transnationally".* Máire Geoghegan-Quinn, European Commissioner for Research, Innovation and Science, November 2013

MARINET2 expands on the success of its predecessor with an even greater number and variety of testing facilities across offshore wind, wave, tidal current, electrical and environmental/cross-cutting sectors. The project not only aims to provide greater access to testing infrastructures across Europe, but also is driven to improve the quality of testing internationally through standardisation of testing and staff exchange programmes.

The MaRINET2 project will run in parallel to the MaREI, UCC coordinated EU marinerg-i project which aims to develop a business plan to put this international network of infrastructures on the European Strategy Forum for Research Infrastructures (ESFRI) roadmap.

The project will include at least 5 trans-national access calls where applicants can submit proposals for testing in the online portal. Details of and links to the call submission system are available on the project website www.marinet2.eu

European Commission

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Disclaimer

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1 Introduction & Background

1.1 Introduction

The Anaconda technology is based on the propagation of internal bulge-waves through a flexible, water-filled tube. The tube is intended to sit just below the water surface and is aligned perpendicular to the oncoming wave front (Figure 1). Dynamic pressure variations applied to the flexible tube by incident ocean waves change the cross-section of the tube at frequencies which initiate an internal bulge-wave. This wave propagates inside the tube in phase with the external ocean wave. The bulge-wave continues to extract energy from the external ocean wave as it grows towards the stern power take off (PTO). The speed of the bulge propagation along the tube is determined by the distensibility of the tube. If this speed is close to the phase velocity of the waves, then there is a resonance and optimised energy transfer between the two. Distensibility is the property relating to the stretching or swelling of the tube and the key control parameter needed to optimise this energy transfer. It is defined as a function of tube working diameter, thickness, percentage of rubber to inextensible material in the circumference and Young's Modulus of materials.

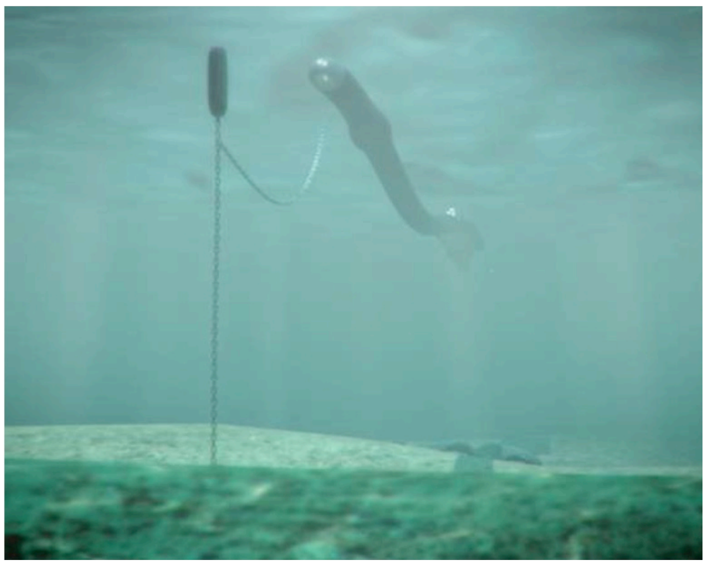


Figure 1: Anaconda Wave Energy Converter in a proposed installation configuration (sub-surface view)

The Anaconda technology embodies a complex hydro-elastic problem directly coupling power performance and survivability in both extreme conditions and fatigue conditions as a result of millions of duty cycles during operational conditions. The governing design parameters of the bulge-wave tube's dynamic response to wave excitation influence this balance between cost, power performance and survivability. Determining how to select the particular design parameters to address this balance and demonstrate economic potential is a key target outcome of current development work.

The use of a wave absorbing mode based on flexible materials is a radical change from other families of WEC devices, with potential for step-change improvements in areas that impact overall LCOE:

- A self-referencing primary absorber based on flexible materials avoids the need for any articulated joints, reference bodies and/or end stops associated with rigid wave activated bodies. This offers potential step changes in reliability and survivability.
- The inflated structure permits the use of new installation and maintenance principles for marine operations offering potentially radical changes to installation and O&M costs.
- The bulge-wave principle for converting wave energy is entirely novel and has been patented by CSL. While impressive energy production and broad-bandedness has been measured experimentally, the full energy production potential is only just beginning to be understood. A key advantage also is that at the point of conversion, only relatively simple damping strategies are required to convert the available power, with no need for more complicated control strategies or reactive forces.

- There is potential for a step change in structural weights and material costs, especially given the future innovation potential in the primary bulge tube design.
- There is a drastic reduction in the criticality of structural failure modes of the primary absorber, relative to large steel structural failures.

The novelty of the Anaconda technology presents substantial opportunities to reduce LCOE of wave energy technology through the significant amount of learning which can be achieved during the continued development and understanding of this concept. This is in contrast to rigid body structures where there are well-established analysis, design and construction techniques but often more limited learning potential in delivering on a pathway to the WES target unit cost of energy.

1.2 Development So Far

1.1.1 Stage Gate Progress

Previously completed: ✓

Planned for this project: ➲

STAGE GATE CRITERIA	Status
Stage 1 – Concept Validation	
• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)	✓
• Finite monochromatic waves to include higher order effects (25 –100 waves)	✓
• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)	✓
• Restricted degrees of freedom (DofF) if required by the early mathematical models	✓
• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)	✓
• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable	✓
• Real seaway productivity (scaled duration at 20-30 minutes)	✓
• Initially 2-D (flume) test programme	✓
• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them	✓
• Evidence of the device seaworthiness	✓
• Initial indication of the full system load regimes	✓
Stage 2 – Design Validation	
• Accurately simulated PTO characteristics	✓
• Performance in real seaways (long and short crested)	✓
• Survival loading and extreme motion behaviour.	➲
• Active damping control (may be deferred to Stage 3)	✓
• Device design changes and modifications	➲
• Mooring arrangements and effects on motion	➲
• Data for proposed PTO design and bench testing (Stage 3)	➲
• Engineering Design (Prototype), feasibility and costing	✓
• Site Review for Stage 3 and Stage 4 deployments	✓
• Over topping rates	N/A
Stage 3 – Sub-Systems Validation	
• To investigate physical properties not well scaled & validate performance figures	
• To employ a realistic/actual PTO and generating system & develop control strategies	
• To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag	

STAGE GATE CRITERIA	Status
• To validate electrical supply quality and power electronic requirements.	
• To quantify survival conditions, mooring behaviour and hull seaworthiness	
• Manufacturing, deployment, recovery and O&M (component reliability)	
• Project planning and management, including licensing, certification, insurance etc.	
Stage 4 – Solo Device Validation	
• Hull seaworthiness and survival strategies	
• Mooring and cable connection issues, including failure modes	
• PTO performance and reliability	
• Component and assembly longevity	
• Electricity supply quality (absorbed/pneumatic power-converted/electrical power)	
• Application in local wave climate conditions	
• Project management, manufacturing, deployment, recovery, etc	
• Service, maintenance and operational experience [O&M]	
• Accepted EIA	
Stage 5 – Multi-Device Demonstration	
• Economic Feasibility/Profitability	
• Multiple units performance	
• Device array interactions	
• Power supply interaction & quality	
• Environmental impact issues	
• Full technical and economic due diligence	
• Compliance of all operations with existing legal requirements	

1.2.1 Plan For This Access

This project closely links to the WES Stage 2 programme of work; the overall objective being to advance the Anaconda technology to TRL4. In order to prove that the developments made as part of the concept design of the Anaconda device during NWEC2 translate into practice, the objectives of the testing are:

1. Testing of 1:25 "all-rubber" tube, configured to be a more resilient design, in performance and survival sea states to determine
    a. Performance and behaviour of an all rubber tube and how the results from the dry-bench testing feed through into the behaviour of the tube during operation
    b. Compare performance of the all-rubber tube to design expectations and tubes tested during NWEC2
2. Measurement of mooring loads and forces in the integrated tether (described in more detail below) in performance and survival sea states, building upon a previous, more limited, campaign at Lir.
3. The testing of novel PTO arrangement for the first time
4. To adhere with best recommended practice (or standards where available) in all testing activities, to ensure that testing outcomes are credible, reliable and verifiable
5. To analyse and interpret the experimental data, applying industry best-practice and scrutiny, and to prepare the testing data for interpretation by subject matter experts (engineering FEED, rubber life cycle, marine operation specialists

Each of the objectives above will feed directly into both enhancing the concept design for the full-scale device and the FEED and subsequent detail design (in stage 3) for the partial scale prototype.

All sensors, data acquisition equipment and device models are available from previous performance testing campaign (also at scale 1:25) undertaken during NWEC2. The ready availability of equipment and the extensive testing experience of the team ensured the above objectives could be fulfilled at excellent value for money.

A prominent example of the design philosophy in survival sea states is the inclusion of an 'integrated tether'. The 'integrated tether' concept comprises two bundles of steel wire (or synthetic rope) cables run along the neutral axis of the tube. These components create a reliable structural connection between the forward mooring system and the aft PTO housing unit. The design intent is to relegate the distensible bulge tube to a non-structural element, so that in either fatigue or ultimate limit states, the criticality of failure is diminished, and tube failures can be considered primarily as commercial risk or LCOE risk, rather than a safety issue. The experimental model will be representative of this 'integrated tether' arrangement, providing evidence of the practical applicability of this approach.

1.2.2 Funding

This testing campaign for the Anaconda WEC was also supported by the Sustainable Energy Authority Ireland (SEAI) under grant OCN107. The SEAI funding was received for model and test preparation. The MaRINET2 funding funded the tank access and the user group travel.

Both the award of the MaRINET2 and SEAI grants are gratefully acknowledged by the Anaconda team.

1.2.3 Note on commercial nature of the project

As the development of the Anaconda WEC is an ongoing commercial project details of the precise nature of the operation of the device and commercially sensitive results have been omitted. The results are, therefore, presented in such a way as to show the progress made during the MaRINET2 testing campaign.

2. Outline of Work Carried Out

2.1 Testing Facility

The testing was undertaken at the Lir National Ocean Testing Facility, Cork (simply referred to as Lir hereafter) in July / August 2018. The Lir deep ocean basin is 35m long, 12m wide and 3m deep. A 12m section of the tank comprises a moveable bed which can be raised to the surface to ease model installation. During testing, the depth was constant at 3m along the length of the tank, giving a full-scale water depth of 75m. This depth is close to that of the proposed full-scale deployment site.

The Lir wave tank was selected for its capability to generate the larger sea states required for the survival testing. Figure 2 shows the Anaconda model installed in the Lir tank. The top photograph shows the performance model setup with waves, and the bottom photograph shows the survival model setup with the tank floor raised

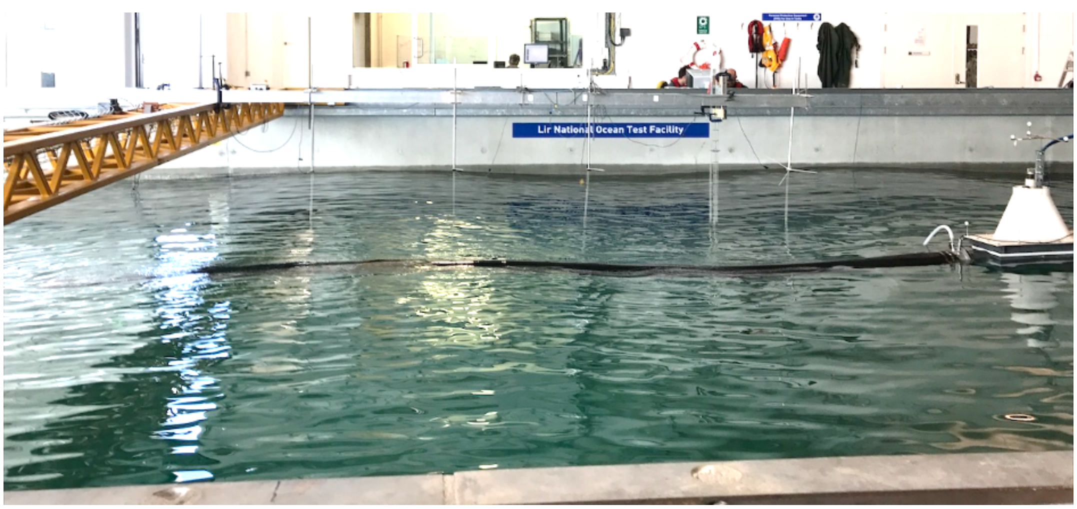


Figure 2: Lir tank with the Anaconda model installed in July 2018. Top: Performance setup with waves. Bottom: Survival set with tank floor raised

2.2 Setup

2.2.1 Overview

The general model setup is illustrated in Figure 3 and Figure 4 showing the principal components.

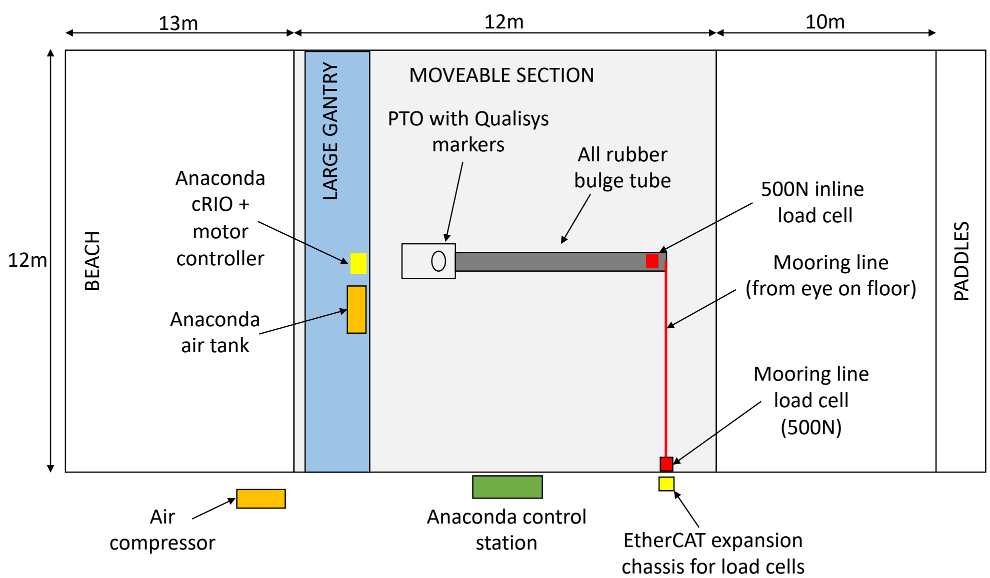


Figure 3: Plan view of the model setup showing principal components. The air tank was used for performance testing only, and not required for the survival testing component

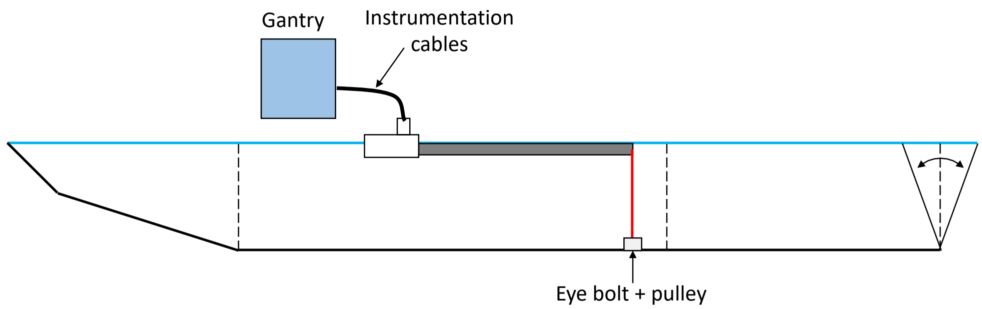


Figure 4: Side elevation of the proposed setup

2.2.2 Bulge Tubes

This testing campaign focuses on the new all-rubber tubes, but a previous baseline fabric-rubber tube was also tested for reference (S1B). The parameters for all-rubber tubes were selected on the following rationale:

i. S1B: Baseline configuration tube previously used in 2018 Strathclyde testing.
ii. CAR1: All rubber version of previous best performing tubes
iii. CAR2: Assessment of diameter reduction at common tuning / static strain
iv. CAR4: Assessment of novel rubber formulation
v. CAR6: Low static strain option at similar tuning to other tubes
vi. CAR7: Multiple thickness to mimic fabric-rubber design only using rubber

Each of the bulge tubes above was bench tested in advance of the campaign (forming one of the overall objectives for the testing) to establish their respective internal pressure to diameter relationship. Using this relationship, the tube is pressurised with water to give a maximum response in waves with a period of between 8 and 10 seconds.

2.2.3 Power take off mechanism

Overview

In order to capture the full set of objectives for the testing campaign, three different designs of power take off (PTO) mechanism are included:

i. Mk2: Linear actuator PTO used successfully during previous NWEC2 testing in Strathclyde (testing in January 2018). This arrangement provides a like-for-like comparison of PTO solution between the fabric and all-rubber bulge tubes.
ii. Mk3: A novel and experimental arrangement of the device to assess potential reduction of forces on the PTO and improved survivability characteristics.
iii. Dummy: A body with representative geometry and mass properties of a potential full-scale device. This dummy PTO is used for the purpose of survival testing only, where no active power conversion is required.

Mk2 PTO

A schematic of the Mk2 PTO is shown in Figure 5. The principal quantities related to the PTO are:

i. The bulge induced force acting on the piston measured by the load cell
ii. The velocity of the piston determined from the linear actuator controller.

With these two quantities the instantaneous power, P, may be calculated as

$$P = FV$$

Where F is the bulge induced force, and V is the piston velocity.

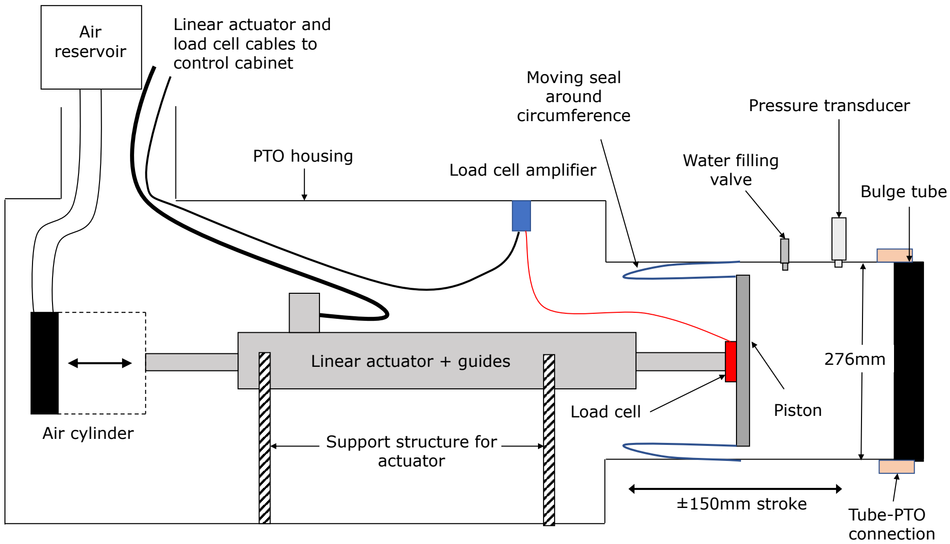


Figure 5: Schematic of the Mk2 PTO

Mk3 PTO

The concept for the Mk3 PTO was developed as part of WES NWEC2, and had not previously been tested.

The key advantage of the Mk3 PTO arrangement is the ability to decouple the surface on which the bulge pressure acts and the PTO mechanism. In survival conditions, the integrated tether can be allowed to go slack. This results in little bulge-induced force on the piston, thereby avoiding the need for the primary PTO mechanism to withstand the harshest conditions.

Dummy PTO

In order to accurately model survival conditions, the Mk2 PTO was replaced by a dummy PTO for survival sea states. The dummy PTO is a scaled version of the full-scale intent, with well-characterised mass and dynamic properties to aide future numerical modelling efforts. The dummy PTO does not produce power and presents a fully reflecting boundary to incoming bulge waves. This represents a worst-case condition in terms of the tube integrity, as large strains are likely to be generated by the superposition of the incoming and reflected bulges.

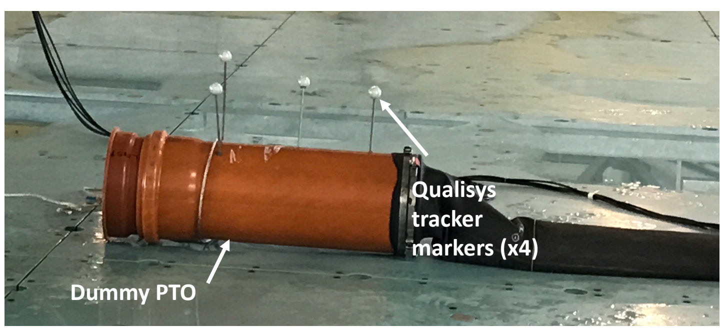


Figure 6: Dummy PTO equipped with Qualisys tracker markers

2.3 Instrumentation and data acquisition

2.3.1 Acquisition system

The custom data acquisition system has been developed by the Anaconda team using National Instruments LabView software, a cRIO and various C-Series modules. The front panel also serves as the input for the PTO control parameters. The interface developed by the test team allowed the simultaneous observation of all sensor data via live displays. The signals which were acquired during the campaign are shown in Table 1, along with the associated C-Series module. All data were collected at 200Hz.

Table 1: Signals for data acquisition system with associated C Series Modules

Signal	Sensor Model	Number	Output	Module
Galinstan strain gauges	Custom	5	mV/V	NI19237
Bulge tube pressure	SENSIT A-AIVAC-0004	1	4-20mA	NI9203
Air system pressure	RSPro 757-5018	1	4-20mA	NI9203
Mooring line load cell	DDEN	1	mV/V	NI9237
Wavemaker trigger	Edinburgh Designs	1	5V TTL	NI9205

2.3.2 Strain gauges

The rubber tube was instrumented with Galinstan strain gauges. These gauges have been used successfully in previous testing campaigns. The strain gauges were connected to the NI cRIO via the 9237 C-Series modules (used as full bridge amplifiers).

The strain gauges were bonded to the non-distensible sections across the rubber sections. Attaching the gauges directly to an all rubber tube poses several challenges, for example in achieving a sufficient bond to last a satisfactory amount of time. These issues were satisfactorily overcome and gauges were carefully calibrated.

2.3.3 Wave gauges

A total of six gauges were used, with all wave gauge data recorded by the Lir tank staff. Five of these gauges were adjacent to the model, with the sixth gauge some way upstream to record the incident conditions in the (near) absence of disturbance from the model.

Table 2: Wave gauge locations from the wavemaker

Wave gauge	1	2	3	4	5	6
Location (m)	7.0	12.25	13.5	14.75	16.0	16.7

2.3.4 Motion capture

As in previous campaigns, the 6DOF motion of the PTO was tracked using the Qualisys motion tracking system available at the Lir tank. A total of four Qualisys cameras were operating, and these were installed on the frame shown in Figure 7. Taken as a whole, the Qualisys motion tracking data were found to be of high quality.

Figure 7: Qualisys camera frame with two camera circles (other cameras not in photograph)

2.4 Mooring arrangement

The mooring arrangement is designed to provide a well-characterised system for integration into future numerical modelling work. The system comprises a high modulus Dyneema line, which is connected to a Ibex Marina Power Spring to introduce compliance into the system. An overview of the system is given in Figure 8.

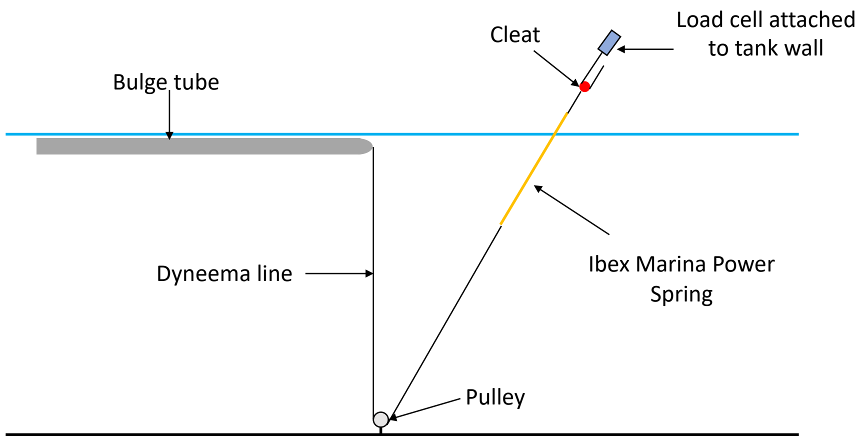


Figure 8: Schematic of the mooring system

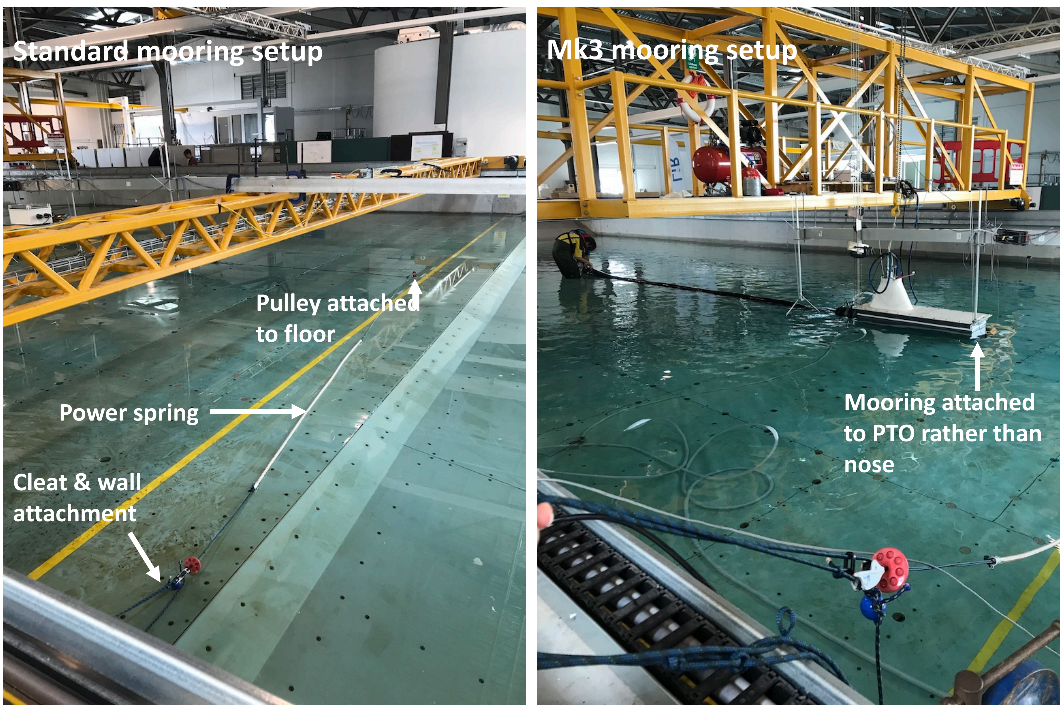


Figure 9: Mooring setup. Left: standard configuration. Right: Mk3 setup where the mooring line is attached to the PTO

2.5 Tests

2.5.1 Performance sea states

The performance sea states undertaken at Lir comprised primarily those specified by WES as part of the NWEC2 programme. This enables like-for-like comparisons with previous testing. These sea states are well within the capabilities of the Lir tank at a scale of 1:25. Each sea state was run for a return period of 630s in line with WES guidance. A number of regular wave cases were also run to provide additional systematic data for numerical model comparisons.

The irregular wave cases are shown in Table 3, and comprise the sea states that have been tested for previous configurations of the Anaconda device to enable cross-comparison. Again, these sea states are in line with WES guidance.

Table 3: Irregular sea states for performance testing, characterised by a JONSWAP spectrum

Index	Full Scale	Model Scale

	Tp (s)	Hs (m)	Tp (s)	Hs (m)
PI01	7.7	1.5	1.54	0.06
PI02	10.5	1.5	2.1	0.06
PI03	13.3	1.5	2.66	0.06
PI04	14.7	1.5	2.94	0.06
PI05	12.6	2.0	2.52	0.08
PI06	7.7	2.5	1.54	0.10
PI07	9.9	2.5	1.98	0.10
PI08	9.1	3.5	1.82	0.14
PI09	10.5	4.5	2.1	0.18
PI10	11.9	4.5	2.38	0.18
PI11	13.3	3.5	2.66	0.14
PI12	10.5	3.5	2.1	0.14

2.5.2 Survival sea states

For the survival cases, the tube was inflated such that it represents a 1:30 model (not 1:25) of the full-scale intent.

The wave cases for the survival seas have been selected using the 50-year design contour. A representative contour for extreme conditions at an exposed Atlantic Coast location is given in Figure 32. At scale 1:30, Lir Cork can deliver up to 14.5m Hs, which is close to the maximum 1 in 50-year Hs at a very exposed location. In practice, a less exposed location would be chosen for first deployment, and 14.5m Hs testing is considered conservative.

The Anaconda rubber tubes are tuned to have maximum response in the region of 7s to 11s, such that survival cases will focus on this region of the return contour. For a peak period of 11s, the maximum 1 in 50-year Hs is reduced to 10m (breaking limited), which can be reproduced at Cork. The longer periods are not anticipated to dynamically excite the tube as much as the shorter periods and are therefore less likely to cause tube breakage.

All survival sea states are characterised by a JONSWAP spectrum with a peak enhancement factor $\gamma = 3.3$ as is common for narrower banded survival seas. The repeat time for the survival irregular waves was 1972s, equivalent to 3h full scale.

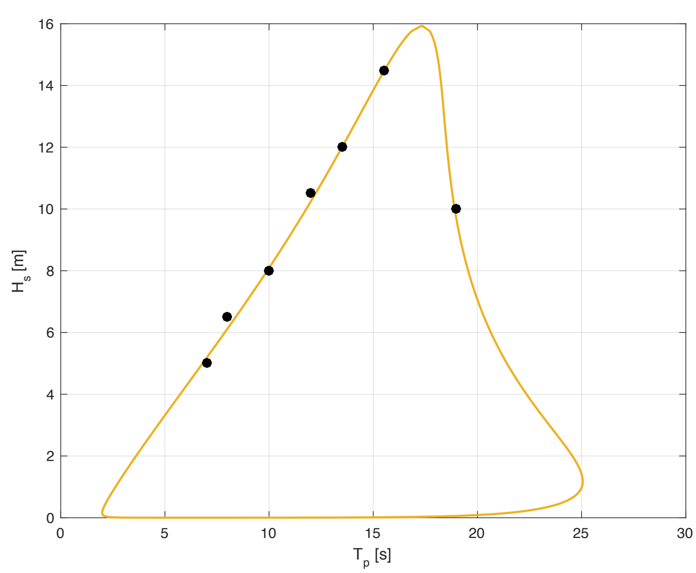


Figure 10: Survival cases showing the 50 year contour (line) of an exposed Atlantic location and the 1:30 survival wave cases undertaken at Lir (points)

2.6 Results

2.6.1 Overview

The presentation of the results in the sections that follow offer an insight into the learning gained during the test campaign. In all, 225 runs were undertaken including:

i. Variations of the absorption control parameters
ii. Locking the PTO piston to directly measure the bulge-induced forces
iii. Power capture for each of the bulge tubes described in §2.2.2 using the Mk2 PTO
iv. Power capture for best performing all rubber tube with the Mk3 PTO arrangement
v. Static pull tests to characterise mooring setup in detail
vi. Survival sea states for an all rubber tube using the Dummy PTO (§2.2.3)

As noted in §1.2.2 the development of the Anaconda is an ongoing commercial project. As such the results presented below aim to demonstrate the improvements made during this campaign without revealing commercially sensitive information. For this purpose, results are presented qualitative (rather than quantitative).

2.6.2 Regular wave power capture

Figure 11 shows gives an example of the operation of the Anaconda device during a regular wave power capture case for tube CAR6. CAR6 was found the be the best performing tube overall. From top to bottom, Figure 11 includes the PTO piston position, PTO piston velocity, the PTO force and the PTO power. By looking at the PTO position it is clear that the passing of a regular wave train along the Anaconda bulge tube creates bulge waves at a regular (or repeating) frequency. These traces are similar to those observed during previous testing campaigns thus demonstrating that all-rubber tubes operate along the same principles as fabric-rubber tubes.

The power trace demonstrates that the almost no reactive power is required for effective power capture as the bulge wave fluid motion is almost entirely composed of active power. This is an important advantage of the Anaconda WEC technology over many other WECs.

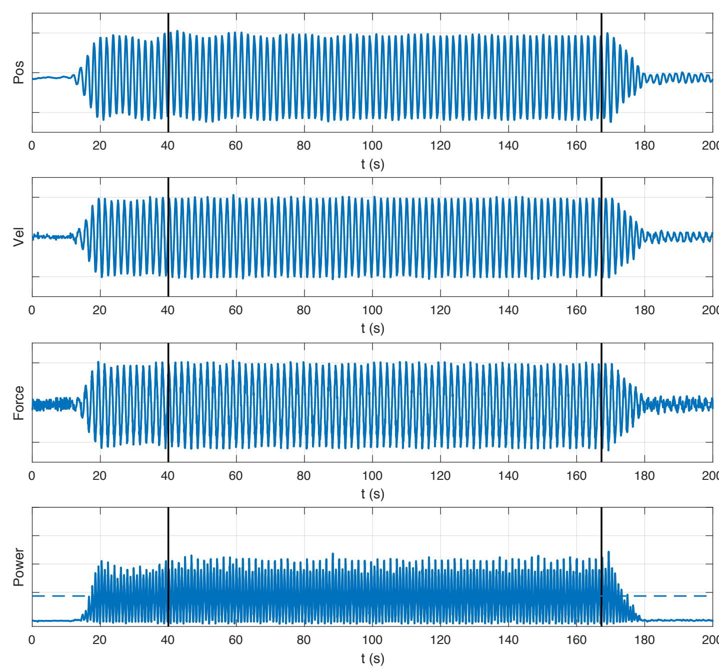


Figure 11: Regular wave example time history showing the position, force, velocity and power

Figure 12 shows a comparison between the power capture of tube CAR6 (all-rubber) and a previous testing campaign which used a fabric-rubber tube. The results were obtained for an identical set of regular waves with height 1.5m and varying period and offers definitive evidence that the performance of all-rubber tubes is comparable to, and may even exceed that of fabric rubber tubes. Furthermore, the performance of CAR6 appears to be more broad banded, suggesting good performance in irregular sea states.

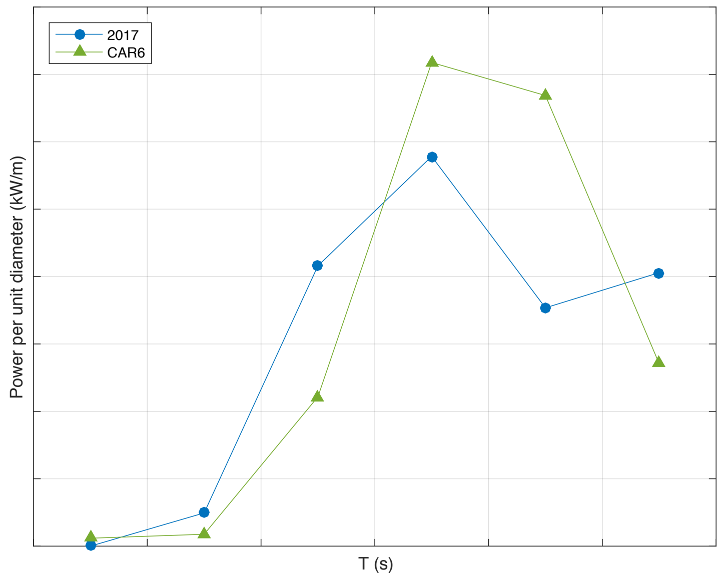


Figure 12: Power performance of tube CAR6 subjected to regular waves normalised per unit tube diameter. Comparison is made to 2017 results of a fabric-rubber tube

2.6.3 Power capture in irregular sea states

Figure 13 shows example time histories for an irregular wave performance case for tube CAR6. The case considered is WES sea state IR7 with Tp = 9.9s and Hs = 2.5m. This is an important case, as it relates to a frequently occurring case in the scatter diagram of common deployment sites. The presentation of data in Figure 13 is equivalent to that in Figure 11, showing the PTO position, velocity, force and power. In the bottom subplot, the mean power is indicated by a dashed horizontal line.

Figure 14 shows the improvements achieved in performance over recent tank testing campaigns in irregular sea states. Clearly the all-rubber tube provides excellent power capture, exceeding previous results of fabric rubber tubes.

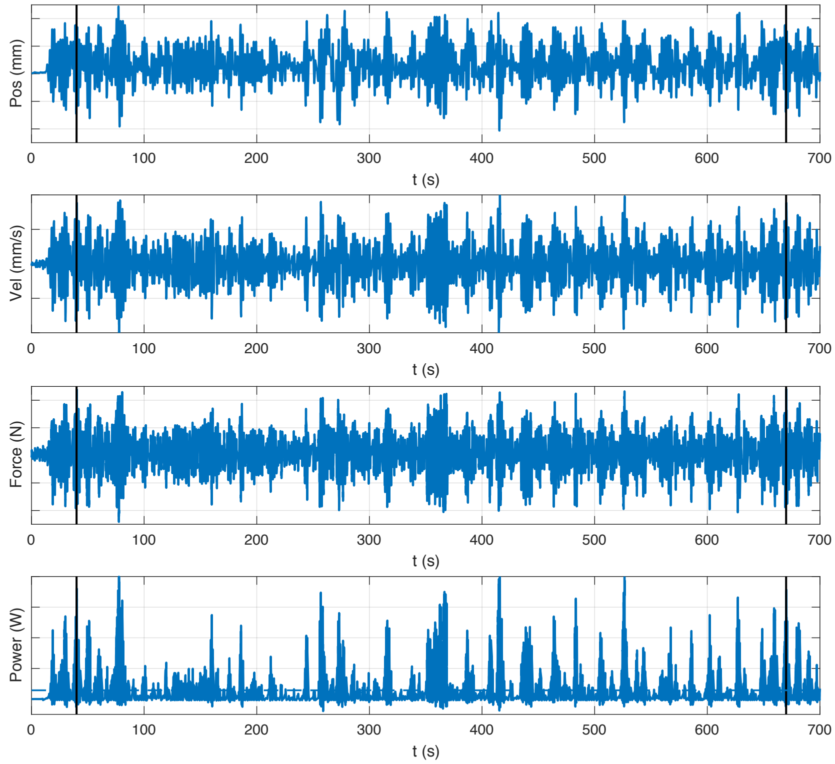


Figure 13: Irregular waves example time history for sea state with Tp = 9.9s and Hs = 2.5m. Subplots from top to bottom include position, velocity, force and power.

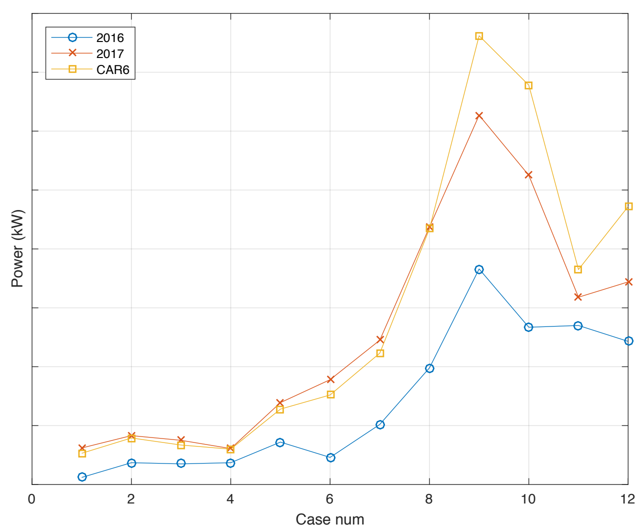


Figure 14: Comparison of CAR6 (Lir 2018) irregular wave performance with previous test campaigns.

2.6.4 Mooring line loads in survival sea states

As previously noted, the evaluation of the mooring line loads in survival sea states comprised one of the primary objectives of the test series. The revised mooring arrangement (§2.4) allows the results presented herein to be replicated in separate numerical modelling exercises.

Figure 15 shows the time history of the mooring line force in a survival sea state characterised by Tp = 15.5s and Hs = 14.5m. There is a mean offset force equivalent to the buoyancy in the nose cone of the device. The asymmetry about this mean arises from the nose of the device following the large wave troughs thereby shortening the length, and consequently a reduction of force, in the IBEX power spring. In the other direction, however, the force in the mooring line system pulls the nose 'through' the large wave crests rather than riding 'over' the crest. As such, the extension of the spring beyond the mean position is not as large as the shortening. It is, therefore, important to ensure there is sufficient buoyancy in the nose cone to provide a large enough offset force to prevent the mooring line from going slack (zero force event) to ensure the longevity of the system.

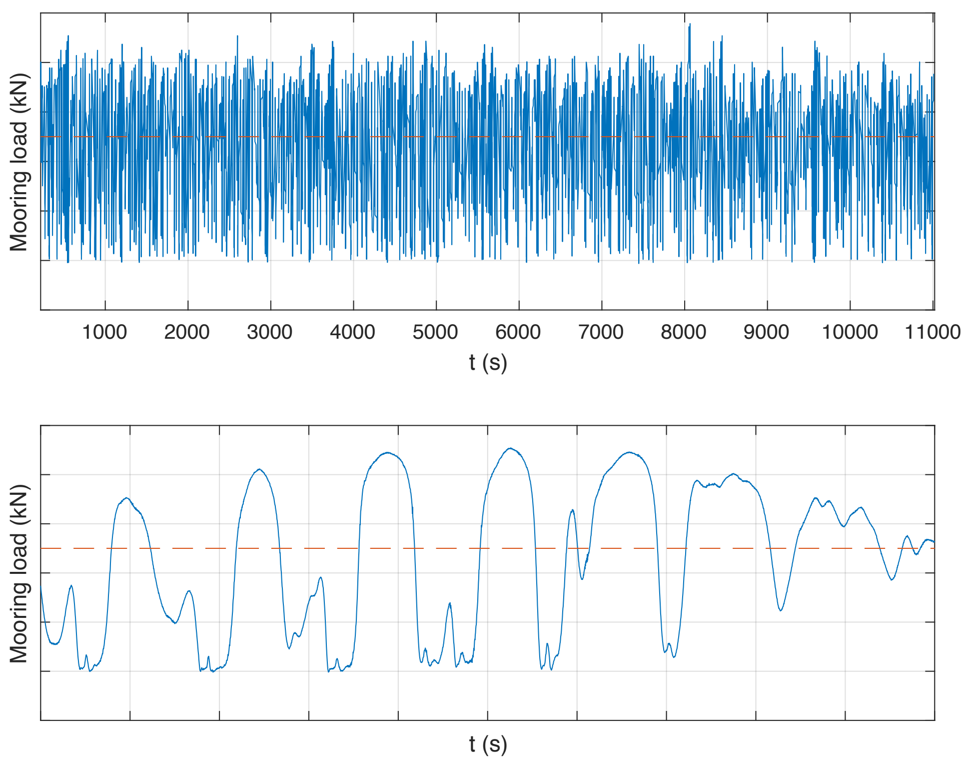


Figure 15: Mooring load time history for survival sea state with Tp = 15.5s and Hs = 14.5m. Dashed line indicates mean mooring load.

2.6.5 Tether loads in survival sea states

Figure 16 shows the time history of the tether force during a survival sea state of Tp = 12s and Hs = 10.5m. Overall the forces have a snatch-like behaviour as would be expected from a non-compliant (stiff line) internal tether. Introducing a compliant line would reduce the maximum loads by an anticipated 30% meaning the present results can be considered conservative estimates for engineering purposes.

The results presented in Figure 16 show the maximum recorded tether loads. Notably, these did not occur in the largest sea state with Tp = 15.5s, Hs = 14.5m. The longer Tp in the largest sea state leads to a reduction in the forcing frequency which appears to avoid snatch loading.

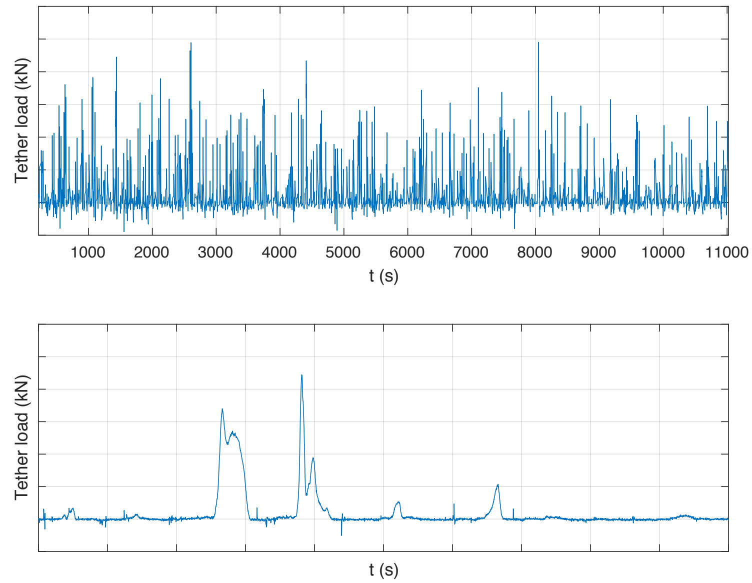


Figure 16: Tether load time history for a survival sea state with Tp = 12s and Hs = 10.5m

2.6.6 Power capture with the Mk3 PTO configuration

The Mk3 setup presents a novel way of configuring the Anaconda PTO and mooring. One of the key Mk3 advantages is that the mooring can be attached to the PTO housing directly, and mooring loads do not need to be transferred via the tube. It should be noted that this was the first time the Mk3 PTO had been tested and was intended as proof-of-concept work.

Nevertheless, Figure 17 shows an example of the PTO signals and demonstrates that the Mk3 PTO solution has the capacity to capture wave energy effectively. The performance of the Mk3 was lower than that of the Mk2 arrangement but the results herein provide a basis for future exploration of the Mk3 concept which has several advantages compared to Mk2. This is an important finding in the context of the MaRINET2 and SEAI funded work.

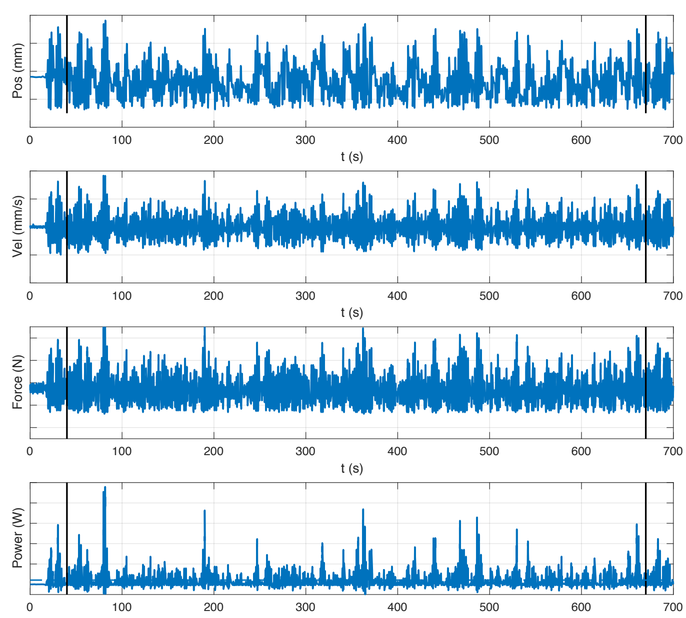


Figure 17: Irregular wave example time history for the Mk3 setup for a sea state of Tp = 10.s and Hs = 1.3.

3. Main Learning Outcomes

3.1 Progress Made

3.1.1 Progress Made: For This User-Group or Technology

The results obtained during the tank test campaign met the objectives originally stated in §1.2.1. Specifically:

1. The results confirmed that an all-rubber tube performs comparably to the previous fabric-rubber tubes as well has having important advantages in terms of manufacturability and longevity in survival sea states.
2. A wealth of mooring and tether loads were gathered allowing for inclusion in ongoing design work and numerical modelling activities.
3. The novel Mk3 PTO arrangement proved a viable means of capturing wave energy and has several distinct advantages over the Mk2 configuration. Further investigation in to the Mk3 concept is likely to lead to cost reductions and improvements to economic case of the Anaconda device as a whole.

Overall the work undertaken at the Lir deep ocean basin under the MaRINET2 grant provides additional confidence to the team to make an application for a Stage 3 Wave Energy Scotland project.

1.1.1 Progress Made: For Marine Renewable Energy Industry

This MaRINET2 funded tank test series provided the Anaconda team with additional learning to take forward into an application for the Wave Energy Scotland NWEC Stage 3 programme. If the team are successful with the application, it sets the Anaconda WEC on a course for full-scale commercialisation.

Several team members are actively involved in the development of the IEC tank testing standard for wave energy converters. The learning gained during this testing campaign will be relayed to the IEC committee to provide advice to the testing of WECs as a whole.

1.2 Key Lessons Learned

The key lessons learnt during this project are:

- Ability of the Lir Deep Ocean Basin to meet survival sea state conditions at a 1:30 scale
- Flexibility of the Lir Deep Ocean Basin staff and their support throughout the series. This includes an excellent movable floor, which facilitated rapid changes to the model, and made overall testing highly effective.
- Extensive experience gains in handling and operating all-rubber bulge tubes
- The benefits of having a simple and easily representative mooring system at tank scale, which may not be representative of the full-scale intent. This simpler system can then be used to validate the hydrodynamics in a numerical model which can later be extended to use a representative system in the knowledge the fundamental dynamics of the device are well known.

4. Further Information

4.1 Scientific Publications

List of any scientific publications made (already or planned) as a result of this work:

- This work will directly support the Anaconda Wave Energy Scotland NWEC Stage 3 application

4.2 Website & Social Media

Website: http://www.checkmateukseaenergy.com/

YouTube Link(s): N/A

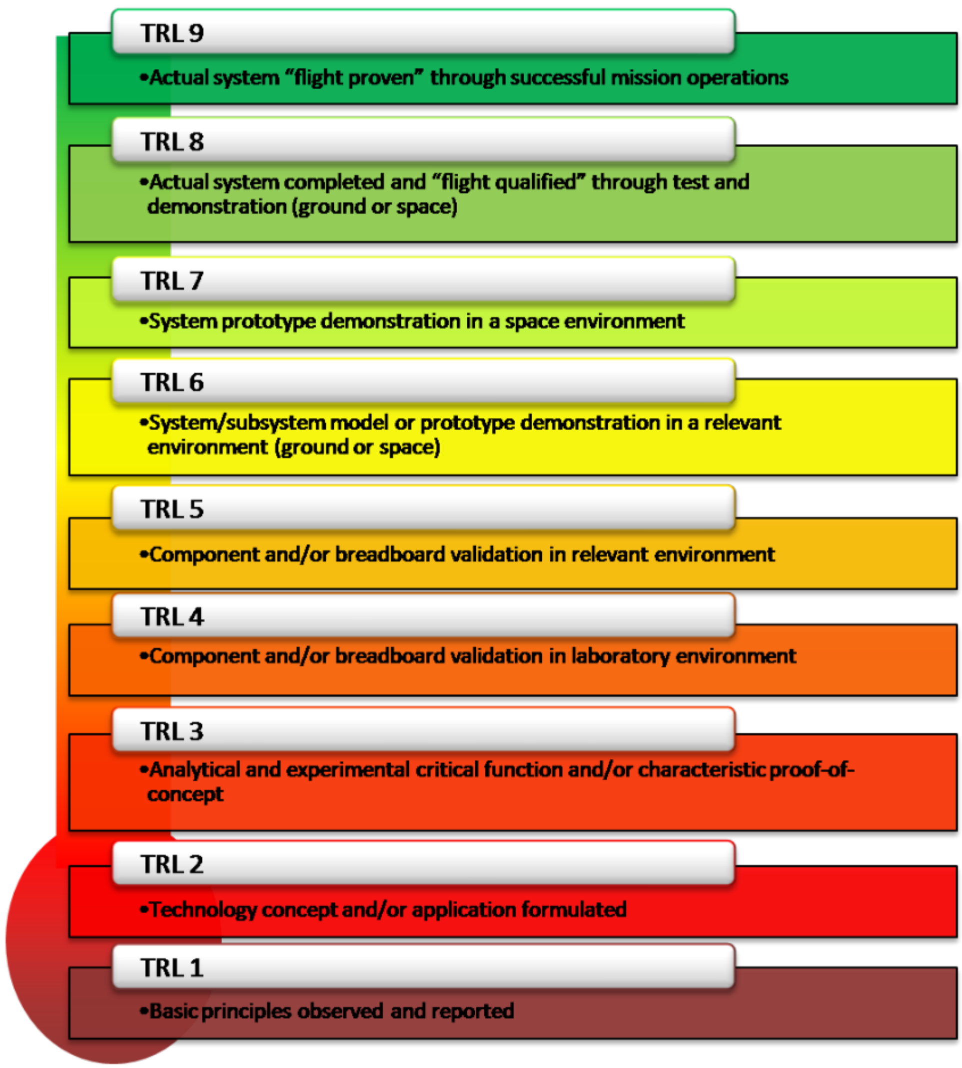
LinkedIn/Twitter/Facebook Links: N/A

Online Photographs Link: http://www.checkmateukseaenergy.com/media/

5. Appendices

5.1 Stage Development Summary Table

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.



NASA Technology Readiness Levels[1]

[1] https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

NASA TRL Definition Hardware Description Software Description Exit Criteria

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modelling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test Performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test Performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results

DEVELOPMENT PROTOCOL	STAGE 1 CONCEPT VALIDATION			STAGE 2 DESIGN VALIDATION	STAGE 3 SYSTEMS VALIDATION		STAGE 4 DEVICE VALIDATION		STAGE 5 ECONOMICS VALIDATION
	TRL 1: Confirmation of Operation	**TRL 2: Performance Convergence**	**TRL 3: Device Optimisation**	**TRL 4: Sub-Systems Assessment**	**TRL5: Sub-Assembly Bench Tests**	**TRL 6: Full System Sea Trials**	**TRL 7: Solo, Sheltered, Grid Emulator**	**TRL 8: Solo, Exposed, Grid Connected**	**TRL 9: Multi-device Array (3-5)**
Objectives/ Investigations	Op. Verification Design Variables Physical Process Validate/Calibrate Maths Model Damping Effect Signal Phase	Real Generic Seas Design variables Damping PTO Natural Periods Power Absorption Wave to Devise Response Phase	Hull Geometry Components Configurations Power Take-Off Characteristics Design Eng. (Naval Architects)	Final Design Accurate PTO [Active Control] Mooring system Survival Options Power Production Added mass	PTO Method Options & Control Inst. Power Absorption Electricity Production & Quality	Scale effects of Overall Performance Characteristics Mooring & Anchorage Security Environmental Influences & Factors	Oper & Mains Procedures Electrical Output Quality Grid Supply, Stability & Security PTO Performance at all phases Control Strategy Seaworthiness, Survival & Lifecycle Analysis Device Array Interaction (Stages 1 & 2)		Grid Connection Array Interaction Maintenance Service Schedules Component Life Economics
Output/ Measurement	Vessel Motion Response Amplitude Operators & Stability Pressure / Force, Velocity RAOs with Phase Diagrams Power Conversion Characteristic Time Histories Hull Seaworthiness; Excessive Rotations or Submergence Water Surface Elevation Abeam of Devices			Motion RAOs Phase Diagrams Power *v* Time Wave Climates @ *head, beam, follow*	PTO Forces & Power Conversion Control Strategies	Incident Wave Field 6 D of F Body Motion & Phase Seaworthiness of Hull & Mooring [Survival Strategies]	Full On-Board Monitoring Kit for Extended Physical Parameters Power Matrix Supply forecasting	Array Interaction Annual Power Prod. Elec. Power Perfm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	$\lambda = 1:25 - 100$ ($\therefore \lambda_e = 1:5 - 10$)			$\lambda = 1:10 - 25$	$\lambda = 1:2 - 10$		$\lambda = 1:1 - 2$		$\lambda = 1:1$, Full size
Facility	2D Flume or 3D Basin			3D Basin	Power Electronics Lab	Benign Site	Sheltered Full Scale Site	Exposed Full Scale Site	Open Location
Duration –*inc Analysis*	1-3months	1-3months	1 3 months	6 – 12 months	6 – 18 months		12 – 36 months		1 – 5 years
Typical No. Tests	250 - 750	250 - 500	100 - 250	100 - 250	50 - 250		Continuous		Statistical Sample
Budget (€,000)	1 – 5	25-75	25-50	50 - 250	1,000 – 2,500		10,000 – 20,000		2,500 – 7,500
Device	Idealised with Quick Change Options Simulated PTO (0-∞ Damping Range) Std Mooring & Mass Distribution		Distributed Mass Minimal Drag Design Dynamics	Final design (internal view) Mooring Layout	Advanced PTO Simulation Special Materials	Full Fabrication True PTO & Elec Generator	Grid Control Electronics or Emulator Emergency Response Strategies Pre-Production	Pre-Commercial	Operational Multi-Device
Excitation / Waves	Monochromatic Linear (10-25Δf) (25-100 waves)	Panchromatic Waves (20min scale) +ve 15 Classical Seaways Spectra Long crested Head Seas		Deployment -Pilot Site Sea Spectra Long, Short Crested Classical Seas Select Mean wave Approach Angle		Extended Test Period to Ensure all Seaways inc.	Full Scatter Diagram for initial Evaluation Continuous Thereafter Time & Frequency Domain Analysis		
Specials	DofF (heave only) 2-Dimentional Solo & Multi Hull	Short Crest Seas Angled Waves As Required	Storm Seas (3hr) Finite Regular As required	Power Take-Off Bench Test PTO & Generator	Device Output Repeatability Survival Forces	Salt Corrosion Marine Growth Permissions	Grid Emulator Quick Release Cable Service Ops	Stakeholder Consult. Health & Safety Issues	Small Array (Up-grade to Generating Station)?
Maths Methods (Computer)	Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion		Finite Waves Applied Damping Multi Freq Inputs	Time Domain Response Model & Control Strategy Naval Architects Design Codes for Hull, Mooring & Anchorage System. Economic & Business Plan			Economic Model Electrical Stab. Array Interaction	Grid Simulation Wave forecasting	Array Interaction Market Projection for Devise Sales
	EVALUATION [Stage Gates]								
Absorbed Power [kW]									
Converted Power [kW]									
Weight, [tonnes]									
Manufacturing Cost [€]									
Capture [kW/tonne] or [kW/m^3]	[200-50 m^3]								
Production [c/kW]	< 25 €c / kW			≤ 15 €c / kW			≤ 10 €c / kW		≤ 5 €c / kW

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