Preparing for AMOG's WEC prototype testing at Falmouth Bay Test site - Advancing Technology Readiness Level

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***Abstract*—A particularly challenging phase in the commercial technology development of wave energy converters is the transition to higher Technology Readiness Levels of level 6 (technology demonstrated in relevant environment) and above. This is due to the required capital investment, installation and operation challenges when deploying technology at sea. 'Nursery' test sites have been established, in order to support this transition, allowing prototype installation and demonstration in relative sheltered environments, whilst offering relevant offshore conditions. AMOG Consulting Ltd are set to deploy their Wave Energy Converter (WEC) device (see Fig. 1) at the Falmouth Bay Test Site (FaBTest). Commissioning will begin at the site in the summer of 2019, following fabrication of a floating WEC system designed at 1/3rd scale for conditions at the FaBTest site. In the time leading up to AMOGs deployment the system design has undergone several iterations to optimise the device for site conditions and the local supply chain. This paper presents the key lessons learned during this period. The paper will be of interest to technology developers, researchers and practitioners, as well as certification agencies and regulators, as it documents the development and preparation of a wave energy converter concept at a nursery test site, seeking to advance the TRL towards a system prototype demonstration in operational environment (TRL7).**

***Keywords*—Wave Energy, Installation, Commissioning, Design, O&M, Device Testing, Wave Resource.**

I. History

WAVE Energy has offered a lot of potential since the first public demonstration of Salter's duck in the 1970s. Despite the offshore engineering experience gained in the offshore oil and gas sector, the marine renewable energy potential has not been realised, yet. The engineering experience can be translated through knowledge exchange, adoption of design/operating standards, and practices from the offshore oil and gas industry.

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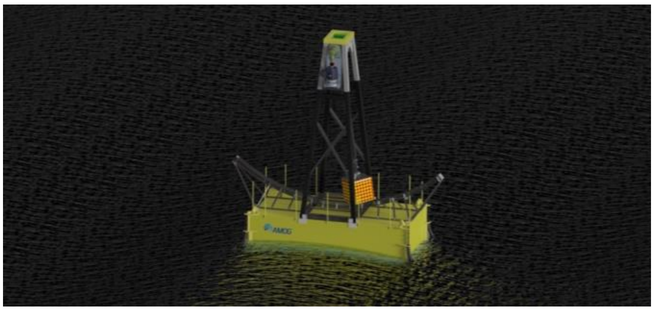


Fig. 1. AMOG Wave Energy Converter Design Drawing

II. Project Background

AMOG Technologies is in the process of developing a Wave Energy Converter (WEC) device. AMOG Technologies has developed a WEC concept, focusing on the following design principles:

- Mechanical reliability
- Survivability
- Low cost of installation
- Low cost to maintain/operate
- Not re-inventing the wheel

The concept behind AMOG's WEC is a dynamic vibration absorber (DVA) or roll stabilisation device. A conventionally tuned DVA system uses a small, secondary mass moving out of phase with the vessel's motions to reduce these motions, with the effect of making the smaller mass (the DVA) dynamic – which is effectively transferring the kinetic energy from the rolling vessel into the kinetic energy of the secondary mass. AMOG's WEC retunes the DVA system to maximise the energy transfer and uses a swinging pendulum as the secondary mass which turns a generator to generate electricity.

III. Phased Development Approach

Development of technology should follow a systematic and staged process. Fig. 2 provides a high level outline of AMOG's planned technology development for the WEC. This is shown by use of the TRL scale (US DOE), and broad phase definitions as follows:

– Phase 1: Proof of Concept
– Phase 2: Technology Demonstration - FaBTest
– Phase 3: Full Scale Demonstrator grid connected – Wave Hub, or EMEC, or SEM-REV
– Phase 4: Roll Out

A. Phase One – Proof of Concept

The AMOG WEC has been developed from concept sketches, utilising the fundamental principles of DVAs. Extensive hydrostatic and time domain hydrodynamic numerical modelling has been performed, with 10 different hull forms trialled and 1000s of models analysed to optimise the damping level, natural period selection and vessel roll period characteristics for different sea states and water depths. Subsequent to numerical modelling, wave tank testing was performed in the largest facility available in Australia at AMC-UTAS. A physical scale model of ~1:30 was used (where the full scale device is 25 m long and the model was ~800 mm long). This testing provided calibration parameters for numerical modelling which carried through to Phase Two.

Initial design of the WEC explored a roll activated power take-off with a deep righting keel. Analysis of the specific conditions at the South Cornwall site led to design of a pitch driven system and tank testing demonstrated the device ability to operate in a range of seas, with subsequent iterations resulting in minor modifications to the vessel shape, and mooring system. Following further computer modelling, reiteration, and tank testing the device will begin fabrication in the UK for a summer deployment.

B. Phase Two - Technology Demonstrator

The design, construction and testing of the 1/3rd scale technology demonstrator is the scope of Phase 2 of AMOG's WEC Project. Phase Two is currently being undertaken, with a planned technology demonstrator of the AMOG WEC at approximately 1/3rd scale. This is planned to occur during the UK Summer 2019 at Falmouth Bay Test Site (FaBTest). The wave energy device will consist of a floating vessel (see **Error! Reference source not found.**) with a spread four-line mooring with drag-embedment anchors. The operations will make use of a small number of small vessels and a non-dynamic-positioning tug vessel.

FaBTest is a 2.8km^2 test area situated within Falmouth Harbour Limits, approximately four kilometres offshore in Falmouth Bay, Cornwall. The nursery facility enables up to three device developers to test moorings, components, concepts, procedures as well as full scale devices concurrently. AMOG's WEC will join the Marine Power Systems WaveSub at FaBTest this summer at the deeper (~50m) end of the site. FaBTest has pre-consented status as a test site, reducing the consenting burden and its moderate wave climate and access to port infrastructure keeping downtime and maintenance costs low. The local supply chain and offshore research expertise, as well as available research funding through the ERDF Marine-I development fund all support this demonstration of marine technology.

The scaled technology demonstrator aims to show the AMOG WEC technology at a pre-commercial scale, and in an ocean environment. Phase 2 focuses on design, engineering, and fabrication. More specifically, this phase aims to:

– Demonstrate power generation in the targeted wave periods at low wave heights (where the test device is predicted to be most efficient).

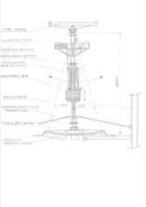
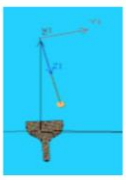
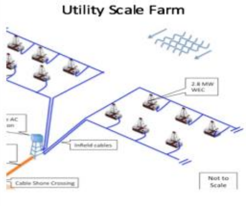
Phase	PHASE 1 PROOF OF CONCEPT			PHASE 2 TECHNOLOGY DEMONSTRATOR		PHASE 3 FULL SCALE PROTOTYPE		ROLL OUT	
TRL (US DOE)	1 Unproven Concept ✔	2 Demonstrate Concept ✔	3 Validated Concept ✔	4 Prototype Tested IN PROGRESS	5 Sea trials System Integrated	6 Environ Tested	7 System Tested	8 System Installed	9 Field Proven
Stage				1:3 scale Benign Site Tests with PTO 		1:1 scale Pre-Commercial Demonstrator 		Utility Scale Farm 	
Duration	Complete	Complete	Complete Factory Test of PTO complete	12 months project (including 4 months data collection) FaBTest Falmouth Bay Protected Harbour		18 months project (including 12 months design & build with 6 months data) Various potential sites including Wave Hub (Cornwall) Sem-Rev (France)		12 months design & build Drive down LCOE as system is cheap, very few bespoke components and lends itself to mass production in existing shipyard facilities.	

Fig. 2. Wave Energy Converter phased development plan

- Demonstrate power generation at longer wave periods in both low and high wave heights (where the test device is subjected to larger incident wave energy)
- Demonstrate the ability to transition between survival and operational modes.

The scaled WEC will be ocean field tested using a basic and robust manifestation of the Power-Take-Off (PTO) system for the purpose of trials. A more sophisticated PTO is under development for the commercial scale WEC devices. During the test period, when conditions are not suitable for the technology demonstrator to be running, the WEC will be maintained in a survival state, and capable of riding out the 20-year return period storm. It is expected that the device will be able to be left in the survival state in between tests, where it can remain unsupervised; transitioning between modes and not anticipated to require external intervention due to a full telemetry and autonomous control system (currently under development).

Much of the detailed design effort of Phase 2 focused on assessing the FaBTest extreme return period conditions and the expected accelerations that the topsides, hull and keel structure would be subjected to. Additionally, predictions of power generation by sea-state for FaBTest were assessed. With these predictions in hand, appropriate sizing of the local power dissipation devices could be made (since FaBTest is not grid connected). AMOG selected to use electrical immersion heaters (passive resistors) that are submerged in a sweater with protective slotted sleeves around them. Air heaters were contemplated as a means of power dissipation, but not selected, as their robustness and capacity to dissipate over 50kW of power would be difficult to achieve in the space available on the WEC.

C. Phase 3 – Full Scale Prototype

Phase 3 is to involve a full-scale grid connected prototype. Early plans are underway with Phase 3 site scoping and selection. The Phase 3 full scale grid connected prototype testing is aimed at:

- Proving the success of the technology with a larger scale, grid connected converter
- Demonstrating high power conversion efficiency across a large range of wave heights and periods
- Demonstrating the solution provides a high availability of power supply
- Managing and automating the system controls

The Phase 3 full scale grid connected prototype WEC will be field tested offshore in an operational environment. The converter will likely feature a low height structure whereby the PTO is mounted on a patent pending rail-cart system without the need for a long pendulum that reaches high into the air.

Power conversion management and system controls will be automated in the Phase 3 prototype. Experimental trials will take place to optimise the conversion system under the widely varying environmental conditions.

D. Phase 4 – Roll out

Roll out of the technology is expected to consist of an array of devices – initially a relatively small number to reduce technical risk. Aspects that will be tested in the first array include inter-array power cabling, mooring of multiple devices and O&M (operations and maintenance). The inter-array power cabling will consist of dynamic power cables taking power from the vessel to the seabed. These challenges are only just being tackled by the offshore floating wind sector. The mooring configuration will explore the most economic mooring configuration for multiple devices which allow unhindered access to the devices. Finally O&M strategies will be tested by exploring the most economic means of providing operation and maintenance support for the WEC devices. Concepts include the ability to 'plug & play' devices – removing them for maintenance to shore whilst not effecting the other devices present.

IV. Stage Gates

AMOG has followed a project execution process which involved the following stage gates:

- Concept
- Front End Engineering & Design (FEED)
- Detail Design
- Execution

E. Concept

The Concept Select Stage Gate involves completing the following activities:

- Concept evaluation report
- Project Execution Plan
- Wave Tank Testing Specifications
- Preparing RFQ (Request for Quotations) for preliminary activities to be performed locally in Cornwall

F. FEED

Finalising the FEED Stage Gate involves:

- Mooring design report
- Hull and Topsides design load report
- Model Test report
- Project risk register
- HSEQ plan
- Electrical systems concept report
- Package for regulatory approval
- System general arrangement
- RFQ for fabricator

1) Design Activities

The following activities have been undertaken in the design process of the WEC. How often these activities are updated depends on the project size and scope.

a) Basis of Design

This should contain environmental site information (seabed, wave, wind and current data, water depth), regulatory requirements, codes and standards, concept of operations, basic properties of the WEC, mooring details, topsides details, power take-off details, telemetry and control assumptions and finally QHSE requirements. AMOG maintains a *controlled* basis of design document so that all engineers have the latest design information and assumptions.

b) Hydrodynamics & Hydrostatics,

To investigate the predicted dynamic response, for operational and survival conditions and to determine statics, both intact and one compartment damaged, to ensure the device does not sink. It is important to understand how much reserve margin is left in the design to accommodate growth in the design as the project progresses.

c) Structural analysis for strength and fatigue

Fig. 3 shows an example of the structural analysis that was undertaken to design the WEC. This figure represents the stresses predicted to occur in the structural members during a 20yr return period extreme survival case. The inertia loading of the equipment on the topsides, as the vessel undergoes accelerations in the sea states, is the primary driver for structural loads in this case.

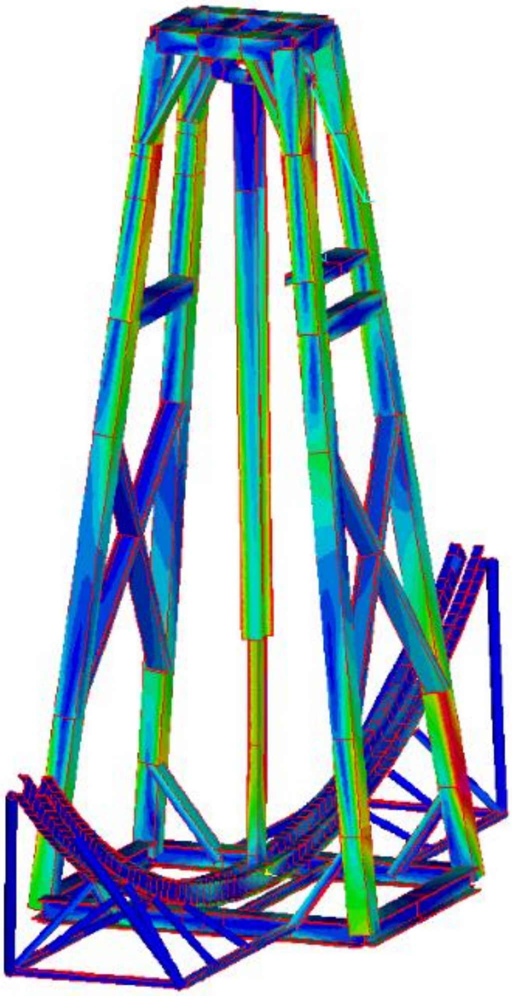


Fig. 3. Predicted structural response of topsides model in extreme conditions where stress is indicated by colour.

Central to the design of the topsides is the recognition that in a highly dynamic sea, a pendulum designed to swing in one plane will experience considerable out of plane loading. To design for out-of-plane loading a curved rail is utilized in which a wheel mounted of the bottom of the pendulum arm runs. Any out-of-plane loading results in the wheel reacting against the rail and relieving bending moments at the top of the pendulum arm and the rest of the topsides structure.

G. Detailed Design

Finalising the Detailed Design Stage Gate involves:

- Hull detailed design report
- Topsides detailed design structural report
- Hull detailed design structural report
- Electrical system detailed design report
- PTO & telemetry acceptance testing
- Operations plan
- Installation plan

2) Modelling

Hull and topsides design require numerical modelling. The approach taken for numerical modelling is illustrated in Fig. 4. Various numerical models of models are required at different stages. The output of the calibration of these models is used in the numerical model of the commercial system to predict behaviour of commercial deployments. Some previous discussion on 'modelling the model' by some of the authors is referenced in [1].

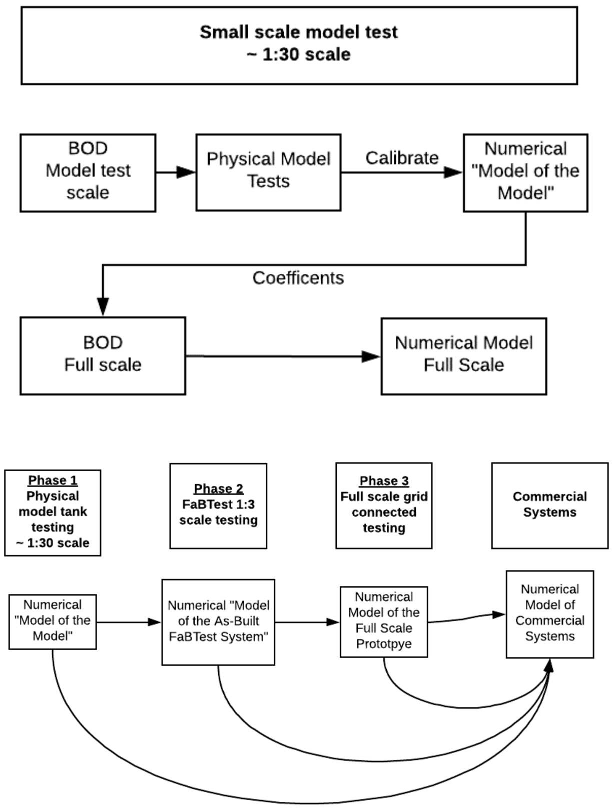


Fig. 4. Numerical modelling stages

Further preparations run alongside the detailed design phase including:

- Equipment List
- Interface register
- Bill of Materials
- Hazard Identification (HAZID)
- Hazard and Operability study (HAZOP)
- Technical Risk Register
- Assumptions Register

The FaBTest trial has, and will involve, procurement of the following non-exhaustive list of products and services:

- Naval Architecture & Drawings Services
- Vessel fabrication
- Ballast supply
- Electrical and Telemetry components
- Electrical load banks
- Electrical generator & planetary gearbox
- Installation services
- Installation aids
- Small vessel hire
- Independent Reviews
- Insurances
- Decommissioning services

H. *Project Execution*

Completion of the execution stage gate involves:

- As-built drawings
- Regulatory approval
- Acceptance testing of the PTO and telemetry
- Load out report
- Inclining testing report
- Operations plan

AMOG Technologies overall philosophy in developing the WEC technology is:

"It's not just the technology, you have to have the right engineering project execution processes"

There have been many examples of past WECs that have failed not because of a poor concept, but because of poor execution in the engineering. Examples include a lack of appreciation of the types of loading that the device may experience. Accordingly this deign builds on oil & gas industry as well as shipbuilding industry best practices to execute the project. This includes:

A Project Execution Plan as a Living Document
Define Roles & Responsibilities
Reporting & Auditing (External & Internal)
Procurement Management
Interface Management
Adopting a Stage Gate Process
Conducting Requirements workshops
Undertaking
Concept Design Reviews
Constructability reviews
HAZID
HAZOP
Maintaining a live Project Risk Register (technical, commercial, regulatory, operational)

V. Preparations for FaBTest

FaBTest is leased and pre-consented, designed to allow flexible and fast access to testing offshore, leaving the developer to concentrate on device and mooring design, and associated procedures. For a trial device, where the objectives are to prove the basic concept of power generation, grid connection is an unnecessary distraction from the primary purposes of the testing.

Environmental conditions continuously measured at the site over a 6 year period, and model hindcast data over a 30 year period were provided to the developer to enable the detailed installation design. With design and project planning complete the developer then applies to FaBTest, informing the regulatory board of project details. This facilitates the necessary due diligence to fulfill the terms of the lease, license, harbor regulations and good practice.

I. Environmental

FaBTest has a mean significant wave height of 0.7m (recorded by Datawell buoy) and a maximum recorded wave height of 10.5m (recorded in January 2018). Fig. 4 illustrates the wave conditions recorded at the demonstration site. The AMOG WEC will be installed for a summer deployment, with milder conditions (mean significant wave height: 0.5m and maximum recorded wave height: 3m).

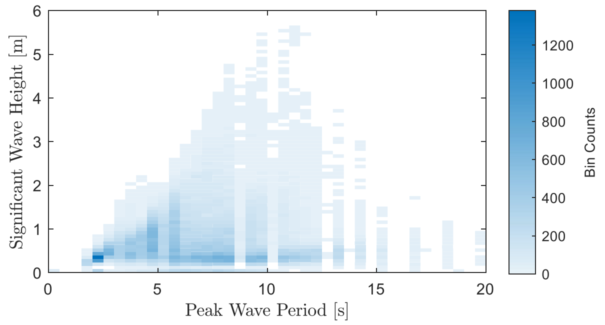


Fig. 5. Significant wave height and peak period scatter diagram for in-situ data from the FaBTest (Datawell) wave buoy [3].

A scatter diagram of the summer wave conditions at FaBTest is shown in

Fig. 5 where darker shading represents a high percentage occurrence. In order to gain useful information from a testing schedule at FaBTest, a device needs to operate in the wave period range of T_e = 4.0 - 6.5 secs. The wave height operational maximum limit can be selected based on factors such as practical engineering limits in the system and structure.

The 1:3 scale FaBTest device, with the frontal length (L = 3.3m) exposed to the incoming wave, is set to produce around 45kW, with the components being designed for 75kW maximum power production.

J. Regulatory

Falmouth Harbour Commissioners (FHC) hold a Marine Licence issued by the Marine Management Organisation (MMO), which licenses certain MEC development test works according to set procedures and conditions. Similarly, FHC has a seabed lease agreement with The Crown Estate (TCE) allowing the use of the seabed, again according to certain procedures and conditions. The Regulatory Body has two permanent members, Falmouth Harbour Commissioners (FHC) and the University of Exeter (UoE). The specific task of the Regulatory Body is to implement a diligence process to establish that each specific FaBTest installation proposal meets with the requirements according to the Marine Licence, FHC regulations, The Crown Estate (TCE) lease and good practice in accordance with stakeholder expectations. In so doing the Regulatory Body advises and informs the decision of FHC to approve or decline an application for a berth at FaBTest. The diligence process includes reviews of the following:

1. *General project overview*
2. *Engineering assessment & general arrangement drawing*
3. *Independent validation of the mooring design*
4. *Quality, Health, Safety and Environment (QHSE) management plan*
5. *Project execution plan*
6. *Decommissioning plan*
7. *Emergency response plan*
8. *Navigational risk assessment*
9. *Seabed habitat risk assessment*
10. *Environmental risk assessment*
11. *Proposal for noise monitoring*
12. *Description of any deviation from the Specification for Navigational Safety*
13. *Insurances*
14. *Security bonds*

These documents have been evaluated through an independent review process. The device mooring has been designed according to API RP 2SK Design and Analysis of Station keeping Systems for Floating Structures. An independent verification of the mooring design has also been carried out, certifying this. The device itself has been designed in accordance with the intent of SOLAS and

Table 1: Return values for Significant Wave Height (Hm0) and Maximum Wave Height (Hmax) at the FaBTest 45m location during summer conditions.

Return Period	H_{m0} with data extrapolated from wave buoy measurements taken in summer (May – Sept incl.).	H_{max} with data extrapolated from wave buoy measurements taken in summer (May – Sept incl.).
1 in 1yr	3.92	6.25
1 in 10yr	4.73	7.55
1 in 25yr	5.05	8.07
1 in 100yr	5.56	8.85

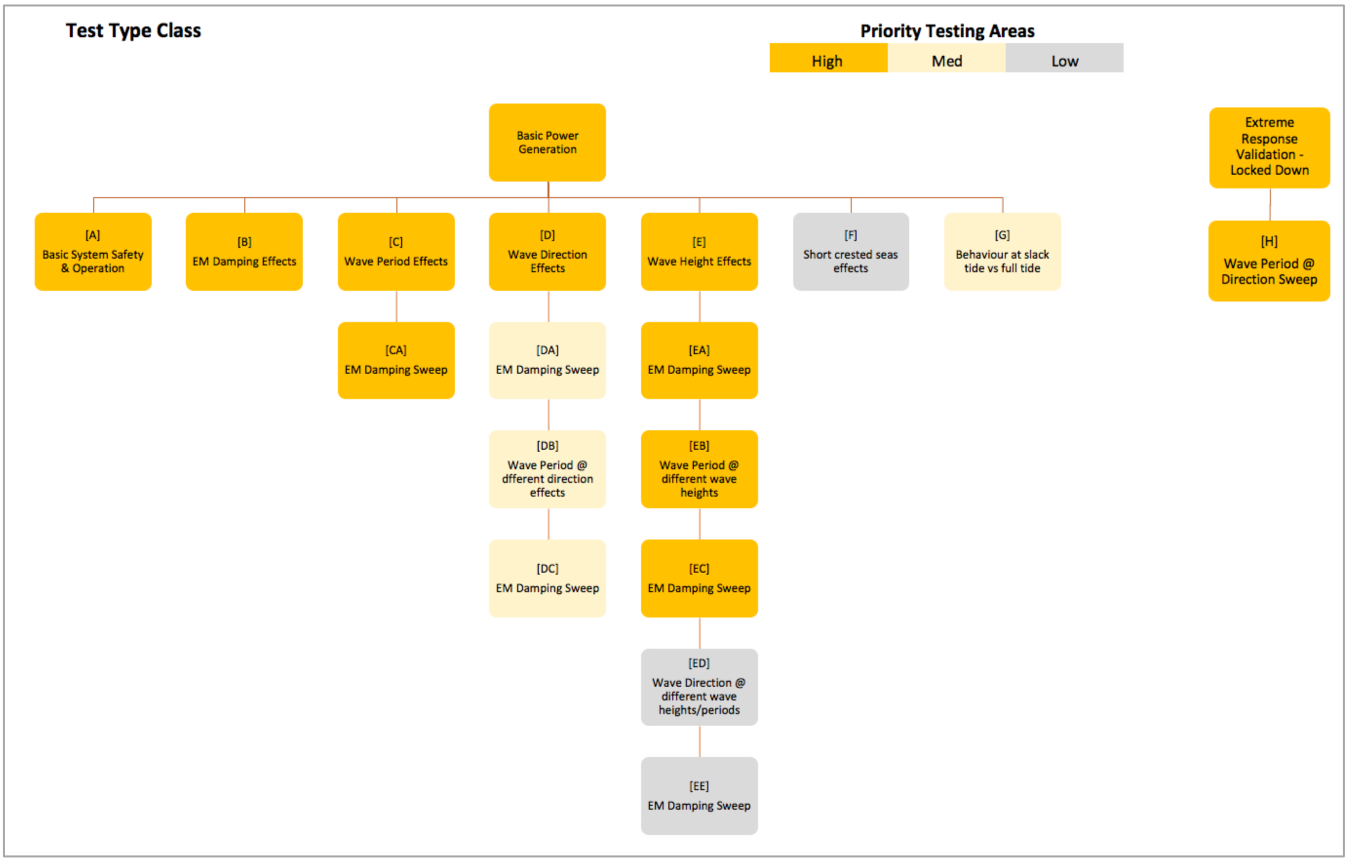


Fig. 6. AMOG WEC outline regime. Testing priority areas for FaBTest 1:3 scale device.

DNV, but is not certified to these standards. Project execution, emergency and decommissioning plans are also under development taking into account navigational risk as well as seabed habitat and environmental risk.

K. *Testing at FaBTest*

Testing at FaBTest is planned to encompass a series of different test types with their respective priorities as shown in Fig. 6 to achieve the desired outcomes. Due to the irregular waves, it takes some time to gather useful response data for each sea state. Test durations of around 30 minutes at each sea state should provide enough useful response information. The extreme conditions are generally described by extremal distributions in the form of return periods. These extreme wave conditions, such as the 1 in 25 year return period significant wave height are indicated in Table 1 below.

VI. Discussion

The specific challenges in developing the AMOG WEC for deployment offshore fall into two classes:

1) General offshore engineering challenges:

- Ensuring the device has adequate under keel clearance at all stages of deployment including launch, harbour transit, tow, onsite and recovery.
- Having a fit-for-purpose economic mooring solution that can be readily installed by any number of marine contractors ensuring a competitive costing basis.
- Being able to transit the vessel in a cost efficient manner, with a simple tow.
- Weight control during design and fabrication.

2) Adequate availability during operations.

Availability is a term used in the processing industry to describe the percent of time that the whole plant is available and can produce. For a WEC there can be a set of engineering constraints that limit the availability. For example, if the wave height gets too large the stresses may be predicted to exceed allowable limits for certain components. The benefit of the nursery site, FaBTest, is that the wave climate is less intense than other test sites. These smaller waves result in an associated smaller structural loading, which for a test device is a more forgiving scenario. Additionally wave period plays an important role in the design of a dynamic system. FaBTest is subjected to generally smaller wave periods than the open Atlantic Ocean. Component loadings are generally less with smaller wave periods but there are resonances which need careful attention in dynamic systems. The AMOG WEC FaBtest device was designed with a constant check on the annualised wave conditions expected at FaBTest such that no single component in the design would unduly penalise the operations time i.e. have a low availability. This included the predicted pendulum swing angle, the length of the pendulum arm, suspended mass, torque ratings of the gearbox and generator, structural loading in the topsides.

VII. GRAND CHALLENGES

In order to create a wave energy industry there are some considerable challenges that the industry as a whole needs to overcome. A workshop was hosted by Marine-I in Cornwall in January 2019. Active contributors to the WEC industry were present including developers, regulators, funders, academics, product suppliers, marine contractors and installers. The workshop presented the following grand challenges:

1) GC 1: Installation, Operations and Maintenance

How to install, service and maintain a system in a high wave energy environment.

Easily disconnect-able systems, switching in spare WECs

The use of pre-laid infrastructure

2) GC 2: Design

Differences to offshore O&G (many units versus single units, reliability)

The creation of industry standard RPs

The availability of shipyards

Composites versus steel

3) GC 3: Exporting Power

Cabling from highly dynamic system

Alternative power export via Hydrogen as a gas, organic liquid or ammonia

Use of intermediary battery storage

The grand challenges were discussed and potential solutions identified. It is expected that these challenges will seed future work.

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