

TECHNICAL SPECIFICATION



**Marine energy – Wave, tidal and other water current converters –
Part 103: Guidelines for the early stage development of wave energy converters –
Best practices and recommended procedures for the testing of pre-prototype
devices**

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.140

ISBN 978-2-8322-5831-6

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**MARINE ENERGY – WAVE, TIDAL AND
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Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62600-103, which is a technical specification, has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
114/233/DTS	114/259A/RVDTS

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62600 series, published under the general title *Marine energy – Wave, tidal and other water current converters*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

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INTRODUCTION

Developing wave energy converters (WECs) will always be a demanding engineering process. It is important, therefore, to follow a design path that will minimise the risks encountered along a route of increasing technical complexity and fiscal commitment. This Technical Specification (TS) presents a guide that addresses these issues, the approach being based on a proven methodology adapted from other technology areas, especially NASA and similar heavy maritime engineering industries.

The scope of the work is defined in Clause 1. Normative references and definitions of important terms are introduced in Clauses 2 and 3 respectively. The core of the document then follows a twin-track approach, relying on:

- a) a structured or staged development approach outlined in Clause 4, and
- b) a set of model specific and goal orientated Clauses 9 to 11 ensuring that targets are clearly defined and attained with confidence. Testing specific requirements such as test planning (Clause 5), reporting and presentation (Clause 6), characterisation of the surrounding wave environment (Clause 7), and data acquisition (Clause 8) are also included.

The structured development schedule makes use of the ability to accurately scale WECs such that sub-prototype size physical models can be used to investigate the relevant device parameters and design variables at an appropriate dimension and associated budget.

The parallel development of mathematical models describing a WEC's behaviour and performance is encouraged, but the procedure is not included in the document.

This document is quite exacting in terms of both the approach and requirements for the development of WECs since it takes a professional approach to the process. Following these guidelines will not guarantee success, but not following them will be a recipe for lost time and opportunities.

MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

Part 103: Guidelines for the early stage development of wave energy converters – Best practices and recommended procedures for the testing of pre-prototype devices

1 Scope

This part of IEC TS 62600 is concerned with the sub-prototype scale development of WECs. It includes the wave tank test programmes, where wave conditions are controlled so they can be scheduled, and the first large-scale sea trials, where sea states occur naturally and the programmes are adjusted and flexible to accommodate the conditions. A full-scale prototype test schedule is not covered in this document. Bench tests of PTO (power take-off) equipment are also not covered in this document.

This document describes the minimum test programmes that form the basis of a structured technology development schedule. For each testing campaign, the prerequisites, goals and minimum test plans are specified. This document addresses:

- Planning an experimental programme, including a design statement, technical drawings, facility selection, site data and other inputs as specified in Clause 5.
- Device characterisation, including the physical device model, PTO components and mooring arrangements where appropriate.
- Environment characterisation, concerning either the tank testing facility or the sea deployment site, depending on the stage of development.
- Specification of specific test goals, including power conversion performance, device motions, device loads and device survival.

Guidance on the measurement sensors and data acquisition packages is included but not dictated. Providing that the specified parameters and tolerances are adhered to, selection of the components and instrumentation can be at the device developer's discretion.

An important element of the test protocol is to define the limitations and accuracy of the raw data and, more specifically, the results and conclusion drawn from the trials. A methodology addressing these limitations is presented with each goal so the plan always produces defensible results of defined uncertainty.

This document intends to serve a wide audience of wave energy stakeholders, including device developers and their technical advisors; government agencies and funding councils; test centres and certification bodies; private investors; and environmental regulators and NGOs.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 62600-1, *Marine energy – Wave, tidal and other water current converters – Part 1: Terminology*

IEC TS 62600-2, *Marine energy – Wave, tidal and other water current converters – Part 2: Design requirements for marine energy systems*

IEC TS 62600-100, *Marine energy – Wave, tidal and other water current converters – Part 100: Electricity producing wave energy converters – Power performance assessment*

IEC TS 62600-101, *Marine energy – Wave, tidal and other water current converters – Part 101: Wave energy resource assessment and characterization*

3 Terms, definitions and acronyms

For the purposes of this document, the terms and definitions given in IEC TS 62600-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1 Terms and definitions

3.1.1

cross-sectional load

compressive or tensile stress parallel to the stress plane and shear stress perpendicular to the stress plane

3.1.2

dynamic

forces responsible for the object's motion

Note 1 to entry: Dynamic side of absorbed power: "Load measurement" (force, torque, pressure, etc.).

3.1.3

kinematic

motion of object, irrespective of how this motion was caused

Note 1 to entry: Kinematic side of absorbed power: "Velocity measurement" (velocity, angular velocity, flow, etc.).

Note 2 to entry: The terms "dynamic" and "kinematic" as defined above are used extensively throughout this document. These terms are used to ensure that a range of WEC conversion concepts are covered. For example, "dynamic" side of load measurement may refer to forces, torques or pressures, and as such provides a convenient and concise means of relating to a range of technologies.

3.1.4

local load

highly localised impacts like green water, slam event or other impacts that could occur due to motion limitations

3.1.5

regular wave

series of waves containing a single frequency component

3.1.6

operational sea state

wave conditions where the wave energy converter is in power production mode

3.1.7**irregular wave**

wave composed of multiple frequency components

3.1.8**peak distribution**

distribution of peak magnitude values

3.1.9**stage 1 <of wave energy converter testing>**

small-scale testing in the laboratory

Note 1 to entry: Stage 1 is equivalent to technology readiness level 3.

3.1.10**stage 2 <of wave energy converter testing>**

medium-scale testing in the laboratory

Note 1 to entry: Stage 2 is equivalent to technology readiness level 4.

3.1.11**stage 3 <of wave energy converter testing>**

large-scale testing at sea

Note 1 to entry: Stage 3 is equivalent to technology readiness level 6.

3.1.12**stationary part of the time series (regular waves)**

interval of the time series in which the wave amplitude and frequency result in repeatable values with small standard deviations

3.1.13**stationary part of the time series (irregular waves)**

interval of the time series used to analyse the spectral shape of the series

3.1.14**storm conditions**

sea state with return period as defined in IEC TS 62600-2

3.1.15**wave train**

laboratory generated series of similar period waves

3.1.16**long-crested waves**

sea state with little or no directional spreading

3.1.17**short-crested waves**

sea state where energy propagation is directionally spread

3.2 Acronyms

CoG	Centre of Gravity
DAQ	Data Acquisition
DoF	Degree of Freedom as defined in IEC TS 62600-1
PCC	Power Conversion Chain. The power conversion chain is made up of a drivetrain, generator, storage, and power electronics.
RAO	Response Amplitude Operator
TRL	Technology Readiness Level
ULS	Ultimate Limit State in the context of structural engineering

4 Staged development approach

4.1 General

This clause introduces the staged development of the design for a WEC through physical model testing. Each stage of development is motivated by risk reduction. The primary goals for each stage address elements that shall be completed before proceeding through the user's pre-defined stage gate for that stage.

Scaled wave conditions produced in the wave tank should be representative of anticipated full scale wave conditions at the expected deployment sites, including sea state spectral characteristics.

Figure 1 shows an overview of the process from the early design concept to the deployment of the first limited device number array. Each stage is based on a different physical scale range carefully selected to achieve a set of specific design objectives prior to advancing the device trials to the next stage. This clause outlines the scope and stage gates for Stages 1, 2 and 3, guiding the development process from Technology Readiness Level (TRL) 1 to 6 (Figure 1). Stages 4 and 5 (Figure 1) concern full scale (or near full scale) testing and are not covered in this document.

This document does not dictate a scale for each of the Stages 1 to 3. The model testing scale heavily depends on the type of WEC developed, the fidelity of the available instrumentation, and to some extent on the availability of appropriate test facilities. The scales provided in Figure 1 are included as indicators of previous WEC development efforts.

Every type of WEC will have slightly different requirements so a bespoke programme should be drawn up around these basic testing requirements. The necessary and recommended goals and experimental activities for Stages 1 to 3 are described in detail in Clauses 5 to 11. Activities are to be defined in the context of good engineering practice, where factor of safety, reliability or other design philosophy are followed.

Although the ordering of the test schedule is of paramount importance, it is equally essential that a stage gate process is applied at the conclusion of each set of trials to evaluate if the WEC has achieved the required experimental objectives before advancing forward. This due diligence should be monitored against the design statement produced by the device developer prior to each stage and the standards being established by the industry based on the other WEC's performances.

A set of Stage Gate criteria for the evaluation of the WEC behaviour and performance at the conclusion of each testing period are defined. These shall be achieved before advancing to the next stage. At this stage of the technology development, the criteria are defined as a general framework and allow for a high degree of flexibility to suit the particular design requirements.

At Stage 1, it should be anticipated that several iterations of a device will be required to optimise the performance, reliability, safety and economics. More than one iteration may still be required at Stage 2, and a single implementation should normally suffice at Stage 3.

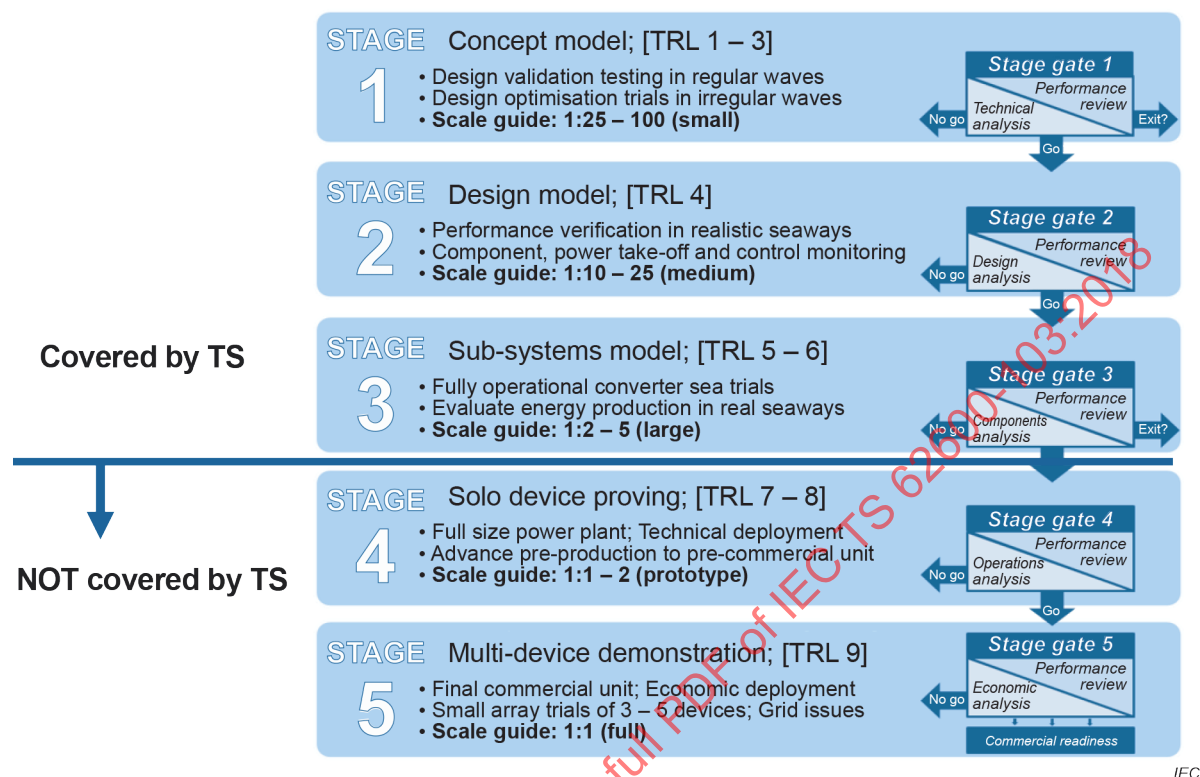


Figure 1 – Staged development approach

4.2 Stage gates

4.2.1 General

At the conclusion of each stage of device model testing, an evaluation procedure should be instigated to assess the overall performance of the design. The appraisal may include a technical and economic review based on three elements of the proposed device design:

- Analysis of the results from the appropriate preceding test programme.
- A comparison with the related device design statement produced at the beginning of the stage.
- An overall design review by a third party, independent, established engineering company.

NOTE See also Annex A for an informative description of the stage gate process.

4.2.2 Criteria

The review shall follow the same set of evaluation criteria at each Stage which are based on the test goals specified for each Stage in Clauses 9, 10 and 11. As the test scale enlarges, the complexity of the model and trials increase to produce more accurate results with less uncertainty in the prototype extrapolation. The Stage Gate evaluation criteria reflect this decreasing uncertainty.

The evaluation criteria shall include

- Energy absorption.
- Device seakeeping (motions).

- Mooring loads.
- PTO loads.
- Ultimate Limit State (ULS) verification.

The minimum specification for each Stage Gate criteria that experimental testing can contribute to are outlined in Clauses 9, 10 and 11 and summarised below.

NOTE Physical model testing is often run in conjunction with a mathematical model development, with model validation criteria similar to the above.

4.3 Stage 1

4.3.1 Scope

Stage 1 is intended to demonstrate that the design has potential and may be realised or transitioned up to TRL3. A key purpose of Stage 1 testing is to explore initial design choices.

NOTE 1 Stage 1 is often used to explore a number of device configurations without a detailed design for the full scale prototype.

There are three facets to Stage 1 tests:

- Proof of concept: to verify that the device design concept operates under wave excitation as predicted and described (under TRL1).
- Optimisation of design: to evolve the most favourable device configuration(s) in regular and irregular waves.
- Device performance: to obtain a first indication of power performance in five sea states for the optimised PTO setting of the device.

All three facets are required to provide input to Stage Gate 1.

For the proof of concept phase of Stage 1, the testing may rely on an idealised physical model. This model can be restricted to a limited number of DoF if this can be justified.

The PTO can be represented by a simplified, but accurate, mechanism. The selected PTO mechanism shall provide a damping that can be characterised across an appropriate range of settings.

A generic station keeping system can be used if the mooring behaviour is not an integral part of the device hydrodynamic motion and energy conversion scheme.

Established ocean spectra can be utilised at this stage to generate the irregular wave excitation time histories, such as Bretschneider, JONSWAP or ITTC.

NOTE 2 At Stage 1, parts of the testing are commonly undertaken using non-natural distributions. This includes white or pink spectra for system identification purposes.

NOTE 3 References [1],[2],[3]¹ provide guidelines for generic test site data, which may assist with the Stage 1 sea state selection.

The methodology of testing recommended here follows the best practice for Stage 1 testing and builds upon the practices developed in [4] and [5]. The results of this stage are lessons used to converge on a full-scale design and data to be validated in the next stage.

¹ Numbers in square brackets refer to the Bibliography.

4.3.2 Stage Gate 1

Energy absorption appraisal shall be based on:

- the set of power response transfer function (RAO, for similar wave heights);
- power capture prospects estimated on a minimum of five selected sea states.

Seakeeping appraisal shall be based on:

- the RAO for the dominant or relevant degrees of motion.

Mooring appraisal if implemented:

- the time series and associated analysis (e.g. RAOs) of the mooring line loads.

4.4 Stage 2

4.4.1 Scope

The purpose of Stage 2 testing is to fully evaluate the device design identified in Stage 1. Stage 2 testing can be associated with a significant amount of design variables, particularly in the PTO description, but shall be based on similar performance indicators as adopted during Stage 1.

Stage 2 testing shall specifically address the following key objectives:

- stage 1 validation: To validate the technical conclusions drawn from the previous test programme and to identify potential scaling issues between the two stages;
- mooring function check: to verify the proposed full-scale mooring and anchorage system design and assess a realistic mooring response;
- device performance: to verify the energy conversion performance;
- device dynamics and kinematics;
- survivability check: introducing storm conditions to observe device response in survival conditions, and to discover device-specific failure modes;
- use the largest scale feasible for available facilities to reduce the influence of scale effects;
- if practical the flexible umbilical electrical cable should be incorporated in selected tests.

It is also recommended that Stage 2 testing incorporates an advanced PTO simulation, exhibiting an accurate representation of the proposed full-scale unit, and introducing a PTO control mechanism by which control strategies can be evaluated.

The primary use of the medium-scale Stage 2 test data shall be to obtain statistically significant values that can be scaled to full-scale values with appropriate factors of safety. The data shall also be suitable to confirm any mathematical or numerical models of the device where available. The data is capable of extrapolation beyond one deployment location.

For validation of the Stage 1 results, both the wave and the device parameters need to be as close as possible to those adopted during Stage 1, adjusted to the Stage 2 scale. It is recommended to include a representative set of conditions, including regular and irregular waves. In selecting these conditions, it is recommended to include the range of each parameter (wave period, wave height and PTO damping) that supported the main Stage 1 conclusions. The medium-scale model may have to be idealised for parts of the test campaign to undertake the comparison to Stage 1 testing. Any deviation between the two Stage set-ups shall be clearly reported.

4.4.2 Stage Gate 2

At Stage 2, the proxy for the annual energy production should be based on a power matrix and site scatter diagram. This type of approach more accurately determines the performance and limits the uncertainty.

Energy absorption appraisal shall be based on:

- the power response transfer function (RAO, for similar wave heights);
- power capture for a minimum of 15 standard sea states (power matrix).

Seakeeping appraisal shall be based on:

- the RAO for the dominant or relevant degrees of motion.

Mooring appraisal if implemented:

- the time series and associated analysis (e.g. RAOs) of the mooring line loads.

4.5 Stage 3

4.5.1 Scope

The motivation for Stage 3 is to identify and address issues of operating in “real world” uncontrolled conditions before risking a full-scale prototype. Stage 3 sea trials are conducted to prove the whole WEC system at a sub-prototype scale to reduce the technical and economic development risk. The test programme should still concentrate on verifying the device power conversion performance in real sea conditions but shall include other validation monitoring, as specified by the design statement.

There are several purposes for conducting testing at this stage, ranging from advanced technical and engineering issues, through deployment and operation matters and including environmental monitoring requirements. The key objectives for testing at this larger scale are:

- deployment check: to test at-sea procedures for deployment and retrieval;
- operational check: to verify expected performance in uncontrolled weather and seas with an electrical load;
- survivability check: to verify failure mitigation strategies;
- galvanic corrosion check: Using alloys representative for the future prototype, to monitor the model for symptoms of galvanic corrosion or stress corrosion cracking;
- fatigue (cyclic) stress evaluation: to install sensors at locations where cyclic stresses may determine system life.

To achieve the Stage 3 objectives, the trials move from the laboratory to an outdoor test site. This means that wave conditions are no longer controllable, or produced on demand, so sea trial programmes shall reflect this and be robust and adjustable to accommodate the naturally occurring sea state. The selected scale should be large enough to include a functioning PTO, electrical generator, power electronics and a downstream energy dissipation method. A low power rated grid emulator can substitute for connection to a grid while eliminating the need for a direct-current system.

The test site and scale should be matched in moored depth, wave heights and periods and any other parameters that affect the device and its subsystems.

A comprehensive sea trial programme shall be developed for Stage 3 that provides sufficient confidence to move towards a full-scale prototype. Tests shall be designed such that they are of adequate duration to enable detailed post-trial inspections to detect symptoms of future cyclic failures. The resulting findings of the trials will provide data as significant as full scale but with a significantly reduced budget and technical risk.

4.5.2 Stage Gate 3

The Stage Gate in this case includes:

- the evaluation/verification of the PTO efficiency and control;
- the evaluation/verification of risk and safety management;
- the evaluation/verification of the power matrix;
- the assessment of environmental impact;
- the evaluation of installation and maintenance procedures and durations;
- the evaluation of fabrication methodology and cost;
- the evaluation of mooring loads and survivability.

NOTE Partial verifications are often undertaken before sea trials commence. For example, it may be possible to evaluate the PTO efficiency and control in a test-stand setup before final device fabrication.

5 Test planning

5.1 WEC similitudes

5.1.1 General

For model scale testing of WECs, perfect scaling would come from:

- geometric similitude for the WEC and its mooring;
- structural similitude for the WEC and its mooring (Cauchy);
- hydrodynamic similitude for the WEC and its mooring (Froude, Strouhal, and Reynolds);
- power Conversion Chain similitude for the WEC.

Since not all of these can be met simultaneously, model scale testing of WECs shall generally be based on Froude and Strouhal similitudes for the hull and structural similitude for the mooring. If other scaling methods are used, then both Froude and Strouhal concerns shall be addressed. The importance of each similitude that cannot be met shall be addressed and documented as the scale-up is completed. Further guidance on similitudes outside of power conversion chain similitude (unique to the testing of WECs) is given in Annex C.

Viscous losses and vortex shedding can be significant at small model scales. To mitigate this, it is recommended to minimise their causes (sharp edges, narrow fluid gaps). Careful assembly is necessary for small models in order to limit magnification of viscous forces that are not expected to be representative of full-scale effects.

NOTE 1 Inaccuracies may be introduced through Reynolds, structural, and power conversion chain non-similitudes for the WEC, and geometric and hydrodynamic non-similitude for the mooring. There are techniques that can specifically address these non-similitudes. However, if they are not addressed, the uncertainty in the scale-up of model data to prototype will be increased. In general, as the Froude scale factor decreases and as the testing progresses in stage, the uncertainty and inaccuracy of scale-up should decrease.

NOTE 2 Density differences between laboratory testing (typically fresh water) and Stage 3 conditions (typically sea water) cause a discrepancy in terms of buoyancy, mass distributions and pressures or forces measured. Hydrodynamic forces are appropriately 2,5% larger in sea-water conditions, and buoyancy may change significantly.

5.1.2 Power conversion chain (PCC) similitude

In general, measuring and scaling the absorbed power is possible for most devices.

Since the WECs response to the environment can be altered through control strategies executed through the PTO, the controls shall also be reproduced at model scale, and hence are considered as part of the PCC similitude.

The PCC is made up of prime movers, generators, storages, and power electronics. Each of these components has efficiencies based on the state of the system, and limitations (such as max voltage or torque values) associated with them. The combination of the prime mover and generator is often referred to as the PTO, and it is often the only item that is represented in Stage 1 and Stage 2 testing.

A specific goal of the Stage 3 testing is to implement a scaled PCC. However, in Stage 2 and Stage 1, it is often not possible to scale the physical components down. Hence representational PTOs that capture the dynamic-kinematic (force-velocity, torque-angular velocity, pressure-flow, etc.) characteristics are often used. However, these representational PTOs can introduce fictional effects, like stiction, or non-physical hysteretic effects. Further, these representational PTOs may not be able to imitate limitations that will exist in the prototype, such as maximum forces or slew rates from the generator.

One major issue surrounding PCC similitude relates to the inability to truly scale bearing surfaces such that frictional losses are also scaled. To improve the predictions of power performance, a friction analysis can be completed to determine the difference in performance that is being lost to the inability to scale frictional losses.

The ability to mimic the prototype control strategy at model scale is very important. The way in which this strategy is implemented is not relevant. However, for Stage 2 and 3, the effect of the control strategy should be demonstrated to be a scaled version of the prototypes through the desired dynamic-kinematic characteristics.

NOTE 1 It is more common for PTO and/or PCC control strategy investigations to be undertaken from Stage 2 onwards.

NOTE 2 Commonly the efficiencies associated with each component of the PCC are dependent on the state of the system. Hence, it is often the case that only the absorbed power (not mechanical or electrical on which these state dependent efficiencies act) will be scaled-up to prototype level.

If the device is an OWC device, special considerations shall be given to the uncertainty of the scale-up since the PTO relies on aerodynamics which is fundamentally governed by Reynolds scaling in addition to being subject to air compressibility.

5.2 Design statement

A design statement shall be available prior to device testing.

For Stage 1 laboratory testing programmes the design statement:

Shall include

- clear statement of the testing goals;
- technical drawing of the experimental device indicating the anticipated scaling factor to full scale;
- description of the experimental mooring system and its anticipated functionality, including position keeping (mooring system does not play an active part in power absorption) or active mooring (mooring system plays an active part in power absorption);
- supporting calculations to provide approximate device physical properties and behaviour.

Should include

- a description of any mathematical device model, where available, detailing how the testing may assist in advancing and refining such model, and verifying that the model includes the governing physics.

May include

- technical advantages and improvements the device introduces over other WECs;
- literature review of similar systems.

For Stage 2 laboratory testing programmes the design statement:

Shall include

- clear statement of the testing goals;
- technical drawing of the preliminary device design in anticipated full scale and the experimental design at model scale;
- definition of the anticipated full-scale PTO and its characteristics;
- supporting calculations to provide approximate device physical properties and behaviour;
- technical drawing of the preliminary mooring design in anticipated full scale and the experimental design(s) at model scale;
- characteristic site conditions for the anticipated device deployment location, including typical wave period, wavelength, water depth and significant wave height.

Should include

- a description of any mathematical device model, where available, detailing how the testing may assist in advancing and refining such model, and verifying that the model includes the governing physics.

May include

- technical advantages and improvements the device introduces over other WECs;
- literature review of similar systems.

For Stage 3, the design statement shall be expanded and shall be based on engineering issues in addition to performance based factors. The design statement shall include:

- clear statement of the testing goals;
- technical drawings and construction procedures relating to the WEC;
- technical drawings of the mooring design;
- control strategies;
- characteristic site conditions for the device deployment location, including typical wave period, wavelength, water depth and significant wave height. Additionally an estimate of the anticipated deployment length needed to sufficiently meet the testing goals;
- characteristic site conditions relevant to understanding system corrosion including conductivity and temperature;
- installation procedures;
- operations and maintenance procedures;
- failures mode, effects and criticality analysis (FMECA).

5.3 Facility selection and outline plan

5.3.1 General

The selection of the test facility or site shall be based upon the minimum requirements outlined for each specific testing goal. These testing goals can often be achieved progressively, requiring an increasingly sophisticated facility and environment. More than one testing goal can be achieved in one testing campaign, and more than one facility can be used to complete each development stage.

5.3.2 Stages 1 and 2

To match the testing environment and the testing goal, the following key facility indicators shall be considered:

- Size of tank and wave generation capabilities to define a suitable model scale:
 - wave height and wave period performance curve;
 - downstream energy absorption capability (for example beach performance);
 - physical tank dimensions, including water depth;
 - connection points and tank footprint for mooring system;
 - model installation, fabrication and setup facilities;
 - regular and irregular wave generation capabilities;
 - long and short-crested wave generation capabilities;
 - long-term wave stability and wave reflections.
- Wind and current capabilities where these are fundamental to the device operation.
- Tank instrumentation and data acquisition.
- Availability of experienced technical staff to run the facility, assist and advise throughout the campaign.

Stage 2 shall also specifically consider:

- The increased scale of the model and the associated change in facility size and wave generation capabilities.
- The role of wind and current interactions, particularly in addressing station keeping and mooring loading.
- The spatial requirements of a realistic mooring system footprint.

Each wave tank is unique in its capabilities and operation, and experienced tank operators shall be consulted. To ensure all important parameters are included, a detailed testing plan shall be devised. Feedback on this plan should be obtained from the facility operator prior to testing. The outline test plan shall specifically consider:

- Time required for model set up and calibration.
- Time required for wave tank calibration or characterisation.
- Number of individual experimental runs, based upon a definition of:
 - number of sea states;
 - number of device design variables and their range;
 - range of regular wave parameters and number of wave spectra.
- Duration of each sea state.
- Tank settling time between experimental runs.
- Number of experiments to be repeated for quality assurance and uncertainty analysis in line with the specific testing goals.
- Device specific test requirements, including sensitivity to directionality and seaworthiness.
- Logical order of experimental runs.

An example testing plan is shown in Annex B.

The wave conditions associated with each specific testing goal differ considerably and are discussed in more detail in Clauses 9, 10 and 11. In all cases, some tests should be re-run to check the repeatability of the test conditions.

NOTE An extensive list of generic wave tank testing requirements is provided in [6].

5.3.3 Stage 3

It is recommended that established sea trial test centres should be utilised to complete Stage 3. When this is not possible care shall be taken to identify a suitable site. The following list of requirements should be considered during the sea zone selection:

- Appropriate spatial and temporal wave condition in both amplitude and period.
- Appropriate water depth for mooring fidelity.
- Convenient launch and deployment facilities, especially vessels.
- Local service and maintenance amenities.
- Land-based data station.
- Appropriate atmospheric and oceanographic conditions, such as the absence of rip currents, hurricanes or excessive suspended sediment.

Site appropriateness will be a device specific evaluation so this list shall be regarded as the minimum requirement. Where necessary the WEC geometric scale should be adjusted to suit the site wave conditions. The minimum scale is only dictated by the requirement that the device PCC is fully operational.

NOTE There are several recognised, official test centres now established in the world. These may be run by a State or private concern. Archive wave data is generally available for these sites, together with other facilities and expertise to assist the device developer.

When the prevailing wave conditions are accepted as they occur, it is essential to develop a test programme that accommodates loss of control. The deployment period shall initially be based on an assessment of the site wave conditions expressed as the occurrence scatter diagram. It should then be adjusted as required to fulfil the full technical programme, including a period of survival conditions.

Stage 3 survival testing is sought to achieve conditions that get close to true survival conditions. Example interpretations of such testing conditions include:

- a) testing that achieves 80 % of the expected ULS;
- b) testing that achieves the worst possible condition for a 1-year period at the Stage 3 deployment location, or
- c) an accelerated exposure of the device to high energy seas at a more exposed site with the proviso that destructive seas may also occur at such sites. Other interpretations are possible and are to be noted in the reporting.

A full test plan shall be produced prior to deployment to ensure all aspects of the design statement are fulfilled. Results shall satisfy the uncertainty criteria specified for each testing goal, in particular the statistical significance for each sea state element of the site wave scatter diagram.

The full sea trial schedule shall accommodate the variability of the wave climate at the site, including parameters such as:

- Spectral profile.
- Multi-modal wave systems.
- Storm conditions.
- Unrealistic seaways.
- Local current.
- Local wind.

Standard sea states can be used, but site specific requirements shall be included in this evaluation where a potential device deployment site has been identified.

5.4 Physical model considerations

NOTE Additional guidance on scaling laws relevant to the physical model is given in Annex C.

5.4.1 Stage 1

The Stage 1 model construction should consider the following:

- The driving forces should be understood to apply the most appropriate scaling law.
- Design to allow individual modification of the key device design parameters.
- Lump ballast to obtain the desired mass distribution.
- Construction material selection (material properties that have a significant impact on the device behaviour shall be scaled, otherwise scaling material properties not required).
- The physical model construction enabling accurate measurements of the key parameters.
- Potential use of limited DoF testing in proof-of-concept where it is expected that this does not significantly alter the fundamental device operation.
- PTO simulation using a simplified, yet accurate mechanism, that has been tested before the experiment for operation.
- Mooring simulation to match desired device dynamics.

Several physical models can be used to complete Stage 1 testing.

5.4.2 Stage 2

The medium-scale physical model shall be less idealised than the Stage 1 model. Supporting calculations shall identify likely failure points, and cross-sectional and local loads. Model design and manufacturing shall enable relevant strain or load measurements at these locations. The Stage 2 model construction should consider all of the Stage 1 suggestions in addition to the following:

- The dynamics of the model should be as close as possible to an exact representation of the full-scale device.
- PTO simulation using representative mechanism capable of exhibiting the proposed full-scale kinematic and dynamic PTO characteristics and control strategy with both aspects experimentally confirmed before testing.
- Mooring system will need to meet both geometric and structural similitude, potentially requiring two designs to meet the goals of this stage.

NOTE Stage 2 models will be significantly more sophisticated than Stage 1 models. As a result, model fabrication and model handling are generally more involved.

5.4.3 Stage 3

The size for a Stage 3 scaled model should be based on the wave parameters found at the deployment/sea trial site and be sufficient to accommodate a fully operational WEC, including the PTO and power electronics pack. For devices above a 500 kW rating, this will still be a significant model on the order of several tonnes and so will require specialised maritime handling. However, due to the power scaling of $\lambda^{3.5}$, the electrical output will be modest, of the order of a few kilowatts. This in turn means the scaled device need not be grid connected and an on-board grid emulator can be used.

The Stage 3 model construction should consider the following:

- Failures mode, effects and criticality analysis (FMECA).

- Identification of ULS loads and factors of safety.
- Identification of key strains within the device structure.
- Accurate and complete assembly procedures.
- Instrumentation needed to record required data streams including sensor redundancy.
- Supervisory control and data acquisition system (SCADA).
- Efficiencies in the power conversion chain.
- Accurate mooring designs and assembly procedures.
- Safety of workers during installation and maintenance.
- Construction material selection.

The device can initially be deployed in a partially built condition to investigate specific design issues, but shall be complete before the sea trial programme is concluded. In particular, a PTO simulation can initially be installed to validate and verify the system hydrodynamics.

NOTE If using full scale materials then a skewed structural scaling will ensue in local load measurements.

6 Reporting and presentation

6.1 Reporting of test conditions and goals

The test planning considerations shall be documented in the reporting. This includes the design statement, testing goals, facility selection and outline plan and physical model characteristics. Special attention shall be given to identification of each similitude that cannot be obtained, which should be included in the reporting along with a description of how this misrepresentation is expected to influence the scaling procedure to full scale. Where the facility characteristics do not entirely match the expected full-scale conditions, this should be noted in the reporting.

The test setup reporting shall identify the still water configuration of the device in the tank, the location of all sensors, and the mooring attachment points. Additionally, all dry and wet calibrations that confirm the device properties, sensor properties, and mooring properties shall be presented.

6.2 Presentation of results

6.2.1 General

After calculating the required performance indicators, as stated in each independent goal section, they should be compiled as model and/or full-scale values as appropriate, and presented in one of three fundamental ways:

- a) as RAO curves with error bars;
- b) in scatter diagrams;
- c) as variable(s) against a set of tested appropriate iso-variables.

The error bars [7] as defined in each independent goal section should be presented with the results. The performance indicators shall be shown in at least one of the fundamental ways, and can also be shown in all of the fundamental ways to elucidate distinct trends.

NOTE It is often helpful to also present subsets of the raw data time series.

6.2.2 Wave parameters

The realised wave parameters, as defined in 7.4, shall be reported.

If required by the design statement, wave scatter diagrams for targeted location(s) shall be reported.

For any irregular wave testing, peak distributions and spectral shapes shall be provided in the reporting. Key statistical parameters include the spectral moments (m_{-1}, m_0, m_1, m_2). Characteristics derived from peak distributions shall include values relevant to the probability density function (Rayleigh, Weibull, most relevant peak distribution), as well as the mean and median values.

6.2.3 Response amplitude operators (RAOs) curves

The relevant RAO curves for the performance indicators should be reported.

Using regular waves, the RAO for individual frequencies should be determined as the ratio between the amplitude of the relevant performance indicator and the amplitude of the characterised incident wave. Error bars should be associated with both the abscissa and ordinate axes. The appropriate uncertainty analysis [7] shall be carried out to establish the error bars to be associated with the final ratio, governed by both the performance indicator standard deviation and the wave amplitude standard deviation. The regular wave RAO curves combining multiple frequencies should be produced for constant steepness sweeps in which, if applicable, the same control settings are implemented.

Using irregular waves, the RAOs should be calculated from the square root of the ratios between the spectral density of the relevant performance indicator and the spectrum of the incident waves (e.g. the square root of the transfer function). When calculating the RAO based on spectra, specific attention shall be placed on the smoothing of spectra prior to calculation of the RAOs, which can only be done by sacrificing frequency resolution.

NOTE 1 RAOs for both regular and irregular waves can be obtained using the ratio of discrete Fourier transforms (DFTs) obtained via the fast Fourier transform (FFT) algorithm.

NOTE 2 In order to obtain reliable RAOs based on spectra, the uncertainty of the individual spectral values is generally sought to be below 15 % (smoothed ordinates or 40-50-subseries (DoFs) in FFT analysis). Furthermore, in order to obtain reliable RAO values, only spectral values larger than 2 % of the peak spectral value (after smoothing) are generally used in the analysis.

NOTE 3 Long period medium energy sea states provide the optimal results in computing RAOs for wave spectra. RAOs can be amalgamated from multiple tests.

6.2.4 Scatter diagrams

The performance indicators and standard deviations relevant to irregular environments should be presented as a bi-variate scatter diagram for the chosen sea states. If required by the design statement, the shading indicating the sea state probability for the commercial deployment location shall be overlaid on the performance indicator scatter diagram. From these, other summary statistics such as the average annual value for the performance indicator should also be identified.

The device power matrix is the most common type of scatter diagram, but other parameters such as device loading may also be presented in this format.

A separate matrix should be developed for each configuration of the device and for any significant changes in the operation of the PTO.

NOTE Optimum power control settings are often established via regular wave trials, and subsequently adopted for irregular wave testing. As a result, an optimised scatter diagram may contain entries relating to a number of control settings.

For Stage 3 sea trials, it may not be possible to achieve a statistically complete power matrix. In this case, iteration and extrapolation techniques can be used to fill in the blank elements, clearly identifying which data are based on direct measurement and which are not.

6.2.5 Alternative iso-variable curves

6.2.5.1 General

When testing was completed in a way that allows for the presentation of the data as iso-variable curves, such as the points of stress concentration against constant wave steepness values, then these curves should be presented. Error bars [7] should be associated with both the abscissa and the ordinate axes.

6.2.5.2 Capture width and capture width ratio

The capture widths for the individual tests shall be calculated on the basis of the absorbed power P and the wave energy flux J , and the capture width ratios shall be derived by normalising the capture widths with a characteristic dimension (typically width) of the tested device, see IEC TS 62600-1 for further definition. The characteristic dimension used shall be clearly stated. The capture widths and/or capture width ratios shall be plotted against key parameters characterising the incident wave field scaled to prototype scale. Typically the frequency domain significant wave height estimate H_{m0} and wave energy period T_e .

NOTE These calculations can be presented at prototype scale or in terms of non-dimensional parameters, e.g. wave steepness, H_{m0}/T_e , and relative length, characteristic device length l normalised by wave length λ_e (based on T_e).

6.2.5.3 Control

Control can be applied in a multitude of ways, from passive linear damping to sophisticated nonlinear active methods. The power performance data shall be presented in a way which clearly identifies the influence of control on the power capture. Control parameters shall be varied such that it is possible to identify the influence of individual parameters on the reported results. If nonlinear control is adopted, the power capture data shall be presented over the full range of the dynamic and kinematic quantities.

6.3 Presentation of performance indicators

6.3.1 General

The characterisation of the performance indicators shall be based on time and/or frequency domain analysis of the time series of the measured quantities. The analysis of the measurements shall be carried out on the same stationary part of the time series; this will also correspond to the part of the time series used to characterise the incident wave field if characterisation occurred without the model present. Sufficient data points shall be used to establish the standard deviation / variability of the requested performance variable.

Processing of the measured variable to produce other quantities of interest, such as velocity and acceleration from position, are encouraged and in some cases required. Signal processing techniques that minimise noise amplified through mathematical conversions should be followed to obtain the most realistic profiles.

6.3.2 Presentation performance indicators in regular waves

Table 1 identifies the statistics that should be obtained for the relevant performance indicators in regular waves.

Table 1 – Presentation of performance indicators (regular waves)

Performance indicators	Stage 1	Stage 2
Continuous quantities (for example WEC dynamics and kinematics)	Average $\pm$ Std. Dev. <Peak> $\pm$ Std. Dev.	Average $\pm$ Std. Dev. <Peak> $\pm$ Std. Dev. <Phase of Peak> $\pm$ Std. Dev. <Peak> to Average $\pm$ Std. Dev. Identify onset of nonlinearity
Discrete events (for example local point loads, greenwater occurrence, slamming and impact events)	Count and identify wave conditions for which event occurred.	Peak magnitude and duration of each event, # of events
NOTE 1 <Variable> refers to ensemble average of the variable.		
NOTE 2 Std. Dev. refers to variability within an experimental run.		

Since it is not possible to produce regular waves in a scaled ocean environment, no regular wave performance indicators are required for Stage 3. All performance indicators for Stage 3 are found in 6.3.4.

6.3.3 Presentation performance indicators in irregular long-crested wave

For irregular long-crested waves, the entirety of the time series used to establish the incident wave field shall be used.

Table 2 identifies the statistics that shall be obtained for the kinematic and dynamic performance indicators in irregular long-crested wave. These statistics shall be obtained for the device position, velocity, and acceleration.

Since it is not possible to produce irregular long-crested waves in a scaled ocean environment, no irregular wave performance indicators are required for Stage 3. All performance indicators for Stage 3 are found in 6.3.4.

Table 2 – Presentation of performance indicators (irregular long-crested waves)

Performance indicators	Stage 1	Stage 2
Continuous quantities (for example WEC dynamics and kinematics)	Average $\pm$ Std. Dev. <Peak> $\pm$ Std. Dev. Peak	Average $\pm$ Std. Dev. <Peak> $\pm$ Std. Dev. <Peak> to Average $\pm$ Std. Dev. <i>Spectral response</i> : indicate the moments of the spectrum <i>Peak distribution</i> : indicate probability density function parameter values, mean, median, and 98 th percentile Directional spectral response if applicable
Discrete events (for example local point loads, greenwater occurrence, slamming and impact events)	Count and identify wave conditions for which it happened	Peak magnitude and duration of each event, # of events
NOTE 1 <Variable> refers to ensemble average of the variable.		
NOTE 2 Std. Dev. refers to variability within an experimental run.		

The spectral response (moments of the spectrum) may include measures such as the standard deviation of the standard deviation. The term spectral response shall be understood

to include sufficient spectral properties (moments) to obtain statistically relevant process measures.

6.3.4 Presentation of performance indicators in irregular short-crested waves

For irregular short-crested waves, the entirety of the time series used to establish the incident wave field shall be used.

Table 3 identifies the statistics that shall be obtained for the kinematic and dynamic performance indicators in irregular short-crested waves. These statistics shall be obtained for the device position, velocity, and acceleration.

Table 3 – Presentation of performance indicators (irregular short-crested waves)

Performance indicators	Stage 2	Stage 3
Continuous quantities (for example WEC dynamics and kinematics)	Average $\pm$ Std. Dev. <Peak> $\pm$ Std. Dev. Directional spectral response <i>Peak distribution</i> : identify 98 th percentile	Average $\pm$ Std. Dev. <Peak> $\pm$ Std. Dev. Directional spectral response <i>Peak distribution</i> : identify 98 th percentile
Discrete events (for example local point loads, greenwater occurrence, slamming and impact events)	Peak magnitude and duration of each event, # of events	Monitoring required if greenwater or slamming was seen in Stage 2. Monitoring recommended if impact event occurred in Stage 2.
NOTE 1 <Variable> refers to ensemble average of the variable.		
NOTE 2 Std. Dev. refers to variability within an experimental run.		

Testing of irregular short-crested waves is not required in Stage 1; hence no performance indicators are given.

7 Testing environment characterisation

7.1 General

The testing environment conditions form an important input for data interpretation and shall be carefully recorded.

7.2 Wave tank characterisation (Stages 1 and 2)

Each wave tank is unique in its operation and wave field characteristics, and the wave tank operator should be consulted to discuss the specifics.

To define the wave field characteristics, one of the following three methodologies shall be adopted:

- calibration of the incident waves undertaken in the absence of the structure;
- if available, wave specifications of previously calibrated sea states in an empty tank provided by the tank operator can be assumed to be accurate if measured in the vicinity of the location where the model will operate;
- the wave field can be measured in the presence of the structure; and might be separated into incident, reflected and radiated (where appropriate) components through data analysis (see, among many others, methods noted in [8]).

The wave characterisation shall take place at or near the model operation location, taking into consideration potential global device motions within the mooring constraints.

If current is to be used in the model testing, the wave calibration shall be undertaken with the current operational.

It is not acceptable to use assumed (or non-calibrated) waves as an input to the analysis. For irregular waves some departures from the target sea state shape are acceptable, and these shall be noted in the reporting.

If significant tank effects (seiche or standing waves, cross-tank oscillations, beach reflections) are observed during the tests, comments regarding their expected influence should be made.

Table 4 identifies the required measurements for each aspect or type of the incident environment.

Table 4 – Environmental measurements

Environmental measurements		Stage 1	Stage 2	Stage 3
Wave	Regular	Deploy at least 2 measurements during tests: in front and one flanking side of the device.	Deploy at least 4 measurements during tests: in front, behind, and flanking each side of the device.	N/A
	Irregular long-crested waves	Deploy at least 2 measurements during tests: in front and one flanking side of the device.	Deploy at least 4 measurements during tests: in front, behind, and flanking each side of the device.	N/A
	Irregular short-crested waves	Not required	In addition to the requirements for the irregular long-crested waves, deploy a cluster of probes capable of resolving the various incoming directions.	Deploy a measurement system within 50m of the edge of the watch circle of the device. This system shall be capable of resolving: frequency, direction, and energy
Current		Monitoring not required	If applicable, monitor using a single probe.	Monitor if current is present,
Wind		Monitoring not required	If applicable, monitor using a single probe.	Wind data from local station or buoy should be recorded

NOTE 1 Waves in tanks are often not spatially homogenous, so it is important to characterise the wave field in close proximity of the device deployment location. For slack moored, buoyant devices that can move about the water surface, particularly in surge, this may be an inexact measurement.

NOTE 2 The purpose of including multiple sensors for wave measurements is to capture any tank variation across the model location.

Early consultation with tank operators is recommended to ensure that the uncertainty associated with the testing environment is considered appropriately in the test planning and subsequent data interpretation.

NOTE 3 All test tanks will introduce a degree of uncertainty in the test results. Given that each tank is unique in its operation, the tank operators are normally best placed to estimate this uncertainty, which will also depend on the specific WEC model dimensions.

If the characterisation is carried out with the model absent, special attention needs to be paid to minimise the reflections of the scattered waves (from the model) which are not present in the measurements used for the characterisation. Thus, this approach is not recommended for testing where the model generates a scattered wave field which can contaminate the incident wave field through reflections at the wave generators, which is often the case if the model occupies a considerable part of the wave tank.

Some WEC types do not directly respond to surface elevation, and calibration of the water surface elevation only may not be sufficient. In such cases, calibration of alternative measures (for example pressures or fluid particle velocities) should be considered.

7.3 Trial site characterisation (Stage 3)

Prior to any sea trial area being designated a Stage 3 test site, an estimation of the prevailing wave climate should be obtained following IEC TS 62600-101.

Real-time monitoring of the oceanographic and atmospheric conditions shall be undertaken for the duration of the sea trials. The location of the measuring gauges shall be carefully selected to minimise contamination of the records from local influences and the device itself.

The data signals can be post-processed but this shall be conducted on a regular, routine schedule to ensure record fidelity.

It is recommended that an established test centre is used for sea trials so that long term wave records are available for test design and planning.

7.4 Wave characterisation

7.4.1 General

The incident wave field (plus wind and current where appropriate) shall be characterised. The wave field characterisations and the terms used in the reporting should be compatible with those defined in [9]. For the purpose of visual inspection, sample time histories of the water surface elevation should also be made available in the reporting where possible.

7.4.2 Laboratory regular waves

For analysis of regular waves, time and/or frequency domain analyses shall be applied. In both cases, the analysis shall be carried out on the stationary part of the time series. Further details on the analysis of regular waves can be found in [10]. Table 5 identifies the required performance indicators.

7.4.3 Laboratory irregular long-crested waves

For analysis of irregular waves, frequency domain analyses shall be applied. This can be complemented by a time domain analysis. In both cases the analysis shall be carried out on the stationary part of the time series. Further details on analysis of irregular waves can be found in [11]. Table 5 identifies the required performance indicators.

7.4.4 Laboratory irregular short-crested waves

For analysis of directional waves, an advanced frequency domain analysis method shall be applied. MLM and/or BDM or similar methods should be used. In all cases the analysis shall be carried out on the stationary part of the time series. The directional wave spectrum shall be plotted and inspected, and should be provided in the reporting. Further details on analysis of directional wave analysis can be found in [12]. Table 5 identifies the required performance indicators.

7.4.5 Sea trials

The wave analysis shall be conducted as specified in IEC TS 62600-101 for Resource Assessment Class 3, Design. The summary statistics and spectral representation shall be calculated for comparison with the corresponding device behaviour data. Any possible contamination of the wave record, such as radiated waves from the device should be noted.

A bivariate sea state occurrence scatter diagrams shall be generated. This table shall be augmented with the ability to identify the wave frequencies and heights (spectral profile) that constitute each wave system summary statistics. Table 5 identifies the required performance indicators.

Table 5 – Environmental performance indicators

Environmental performance indicators		Stage 1	Stage 2	Stage 3
Wave	Regular waves	Wave height H , $\pm$ Std. Dev. Wave period T , $\pm$ Std. Dev. Wave direction θ , $\pm$ Std. Dev.		N/A
	Irregular long-crested waves	Significant wave height, H_s Zero up-crossing period, T_z Energy period, T_e Peak period, T_p Wave direction, θ Repeat time (if any) Spectral shape		N/A
	Irregular short-crested waves	As irregular long crested waves, but including directional spreading		
Current		Not required	If required, speed, profile, and direction	Surface speed and direction; two other monitoring points in the column (speed and direction)
Wind		Not required	If required, speed and direction	Speed and direction ~10m above free surface
NOTE Std. Dev. refers to variability within an experimental run.				

For periodic derived sea states (finite repeat time based on inverse fast Fourier transform) the unique time series duration shall be specified. For fully random generation techniques (white noise filtering), the water surface time history should be saved for future trials.

For additional details on Stage 3 environment characterisation, this TS refers to the methods established for open-sea characterisation in IEC TS 62600-101.

8 Data acquisition

8.1 Signal conditioning

The electrical sensor signals shall be recorded as raw as possible, without any substantial filtering or smoothing at the acquisition stage. Aliasing shall be avoided.

Special attention shall be paid to sensors that supply small output signals (voltages in the order of mV), as these are susceptible to contamination from electrical background noise (large motors, pumps, or wavemaker drives). To ensure that the sensor signal is contamination free, one of the following approaches should be adopted:

- The sensor lead should be kept short (0,5 m to 2 m) and the analogue to digital (AD) conversion should be undertaken in close spatial proximity to the sensor.
- An instrumentation amplifier should be placed close to the sensor, providing signal amplification to a minimum of 1 V peak to peak.

- c) Where longer cables are necessary appropriate measures shall be taken to minimise errors due to noise and damping of signals, e.g. by use of twisted and shielded pairs of wires and/or use of measuring methods employing long cable compensation, such as 6 wire setup for full-bridge strain gauge measurements.

The DAQ sensor suite should include all necessary measurements to assess critical sensor quality. For example, sensors that may have a sensitivity in their output to other factors such as temperature or vibration, may need to be corrected for these factors. Thus, these additional factors would need to be recorded as well.

Noise issues may also be mitigated through the use of instrumentation with current based (typically 4 mA to 20 mA) outputs.

8.2 Sample rate

Most signal frequencies occur below 5 Hz, so a sample rate in the range of 50 Hz to 100 Hz shall be considered sufficient in recording surface elevations, mooring forces and device motions, including velocities and accelerations. Special attention shall be paid when recording localised impact forces, loads, or pressures, where the signal rise time at laboratory scale is in the order of several milliseconds. Sample rates in excess of 10 kHz should be adopted if e.g. impact loads or snap loads in mooring lines are of concern. In such situations, and where large amounts of sensors are deployed, special attention shall be given to ensure the necessary data throughput of the DAQ is available.

NOTE The appropriate data acquisition rate may be affected by the testing scale. Velocities can be higher at the later Stages due to distance being a direct scale whilst time is the square root.

8.3 Analogue to digital conversion and DAQ system

In undertaking the AD conversion, an appropriate measuring range and resolution shall be selected. To ensure maximum conversion accuracy, the minimum range that does not lead to signal saturation should be selected (for example ± 10 V for a sensor that provides outputs in the ± 10 V range). For matching signal and measuring range a minimum of 12-bit resolution in the AD conversion shall be used. A signal range lower than the measuring range is only allowable if the resolution in the AD conversion is correspondingly increased in order to effectively obtaining the same of better signal resolution. Generally, it is recommended to use the highest available resolution.

8.4 Frequency response

The frequency response characteristic of any sensor shall be considered. Special attention shall be paid if sensors are calibrated statically (for example a force calibration using a static weight), and then used to record dynamically varying physical quantities (for example the impact load). The frequency response of the sensors shall be known and shall be documented, ideally stating the -1 dB cut-off frequency. If the frequency response of the sensor is unknown, a dynamic calibration is recommended.

8.5 Data synchronisation

All PCC signals shall be recorded using the same DAQ system. All other signals shall either be recorded using the same DAQ system or, where this is not possible, be synchronised using a common trigger or time base. The time constant of the system and excitation source will determine the accuracy of the synchronisation. A decision shall be made as to the order of magnitude of the phase lag between channels compared with the measurement of interest (e.g. wave period). Lags between DAQ systems (e.g. optical sensors vs. analogue sensors) may misalign samples. This should be checked during testing and evolve an estimate of inaccuracy. This should also be considered when calculating derived values based on data from multiple DAQ systems, which should generally be avoided.

8.6 Data recording

Data shall either be recorded in its raw format (commonly tab or comma separated text) or using binary compression. Unless the amount of generated data is prohibitively large, raw text format is recommended for ease of processing.

8.7 Recording of supplementary test data

All files shall be stored using a systematic and traceable file naming convention. Supplementary data relating to each experimental run shall be recorded as part of the file header data or within an accompanying spreadsheet. This supplementary data should include:

- Purpose of the experiment.
- Name of person undertaking experiment.
- Time and date of the experiment.
- Time and date of the last sensor calibration.
- Target wave height, period, direction.
- Water depth.
- If applicable, speed and direction of wind and currents.
- Location of sensor(s) relative to a well-defined coordinate origin.
- Name and physical unit of each of the signals recorded.
- If a spreadsheet is used, name and location of any associated data files.
- Any additional (visual) observations made during the experiment.

It is recommended to take photographs of the experimental setup at all stages (before, during and after the experiment). The photographs should, if possible, clearly show the location of all sensing equipment. In addition, the experimental runs should be video recorded. A time stamp on the video recordings should be included for synchronisation with sensor data.

NOTE Placing an LED connected to the main DAQ trigger in the field of view of the video camera provides a convenient synchronisation measure.

8.8 Calibration factors

The relationship between the recorded signal unit (for example voltage) and the actual physical property (the calibration factors) shall be documented.

8.9 Instrument response functions

In special cases, instrument response functions or compensation factors of non-ideal test conditions may be required. Any such factors or functions shall be clearly documented.

8.10 Health monitoring and verification of signals

A rigorous health monitoring of all data shall be undertaken including, but not limited to, the identification of:

- Outliers.
- DAQ range saturation.
- Sensor range saturation.
- Significant amount of electrical noise.
- Drastic or unexpected signal gradients.
- Signal bias and drift.

The health monitoring shall be undertaken on a frequent basis, ideally as the experiment is on-going (for example during the tank settling time). If any of the above effects are observed, the issue shall be resolved as quickly as possible, repeating the affected experimental run(s). If this is not possible, any significant sensor / DAQ issues shall be clearly documented.

8.11 Special data acquisition requirements for Stage 3 sea trials

It is essential that the collected raw data is verified on an ongoing basis since repeating trials will be difficult. All time stamped records shall be organised and archived as recommended in IEC TS 62600-100.

The type, number, location, and acquisition frequency of the monitoring sensors shall be tailored to the type of WEC and PTO under test. The key requirements dictating the instrumentation pack shall be:

- Redundancy of essential sensors.
- Alternative route monitoring options.
- Data collection or control strategies.

9 Power performance

9.1 Testing goals

The power performance testing shall produce an estimation of the power produced by the WEC. In Stage 1 the WEC's power production will be primarily investigated through the use of regular waves to produce a capture width curve (RAO). In Stage 2 an experimental power matrix will be produced, sufficiently populated such that an estimate of annual energy production is possible. In Stage 3 the actual power matrix will be sufficiently populated using scaled PCC as opposed to a representational one.

The power performance testing shall also provide sufficient data enabling definition of the error bars for each of the relevant parameters (Annex D).

NOTE Power performance testing in Stages 1 and 2 is often done in concert with kinematics and dynamics in operational environments.

9.2 WEC and mooring similitude

For the purpose of power performance trials, the scaled device parameters shall be matched as outlined in Table 6.

Table 6 – Power performance testing similitude

Geometric similitude	Stage 1	Stage 2	Stage 3
WEC	Major properties of profile scaled to match the produced environment to within 15 %. Constrained DoF testing allowed	Major properties of the profile scaled to match full-scale design to within 5 %	All properties of the profile scaled to match full-scale design within 3 %
Mooring	Full layout (footprint) not essential	Full layout (footprint) not essential	All dominant properties required and scaled to match prototype parameters
Structural similitude	Stage 1	Stage 2	Stage 3
WEC	Not essential unless fundamental to power conversion	Not essential unless fundamental to power conversion	Where possible, match the full-scale materials and construction techniques, even if this will result in skewed scaling for the structural response
Mooring	Properties proportional to distances and scaled pre-tension in at least the dominant DoF scaled to match the produced environment to within 15 %	Properties proportional to distances and scaled pre-tension scaled to match the produced environment to within 5 %	All dominant properties relevant and scaled to match scaling parameter

Typical Froude scale factors at Stages 1 to 3 will result in incorrect Reynolds scaling; if any special techniques are employed to alter the Reynolds regime, these should be documented. Annex C provides additional scaling guidance.

9.3 Power conversion chain similitude

9.3.1 General

The PTO and remaining part of the PCC representation shall be aligned with the specific testing in Stages 1 to 3 as noted in Table 7.

Table 7 – Power conversion chain (PCC) representation

PCC similitude	Stage 1	Stage 2	Stage 3
Drivetrain	A mechanism should be used that will result in a representative and mostly modellable response. PTO implementation: friction based or linear with velocity; Quadratic if an orifice plate is used	A mechanism should be used that will result in a representative and fully modellable response. PTO implementation: Friction based, linear or non-linear with velocity or PI, PID, MPC.	Exact mechanical equivalent in type and scaled to match prototype parameter
Generator			Exact generator equivalent in type and scaled to match prototype parameter
Controls	Simplified controls; Coulomb or linear damping	Controls equivalent in operation; however, aspects relating to time within the algorithms may require special treatment due to scaling. Can be Coulomb, ideal linear, higher order and/or (re-) active control	Exact equivalent in operation
Power conditioning	Not required	Not required	Grid emulator or grid

For devices based on a hydrodynamic to pneumatic power conversion (such as OWCs), special care shall be taken in considering the appropriate scaling laws.

During scaled testing, care shall be taken that losses are reduced before the point of measurement. Special attention shall be given to reduce friction in bearings and other elements of mechanical designs.

NOTE 1 Adopting Froude scaling, power scales with $\lambda^{3,5}$, where λ is the length scale. As a result, a Froude-scaled 1 MW full-scale device yields ratings between 7 W (1:30th scale) to 0,1 W (1:100th scale).

NOTE 2 Where pneumatic power conversion is required, a direct scaling of the air volume following Froude law will introduce differences between the model and prototype behaviour due to air compressibility. This is commonly overcome by modifying the volumes above the water line, especially in case of fixed OWCs.

9.3.2 Stage 1

The size of the small-scale model is commonly such that a scaled-down version of the prototype PTO cannot be adopted. A generic PTO description can be used. It is not required to produce electrical energy. A system shall be developed that is capable of energy dissipation with a known relation to the primary motion.

If the full-scale PTO characteristic is unknown, a generic PTO simulation can be used, which shall be noted in the reporting.

A set of fixed step, passive PTO simulators can be used. The PTO damping shall range from zero (disconnected) to infinity (fixed) and focus on the optimal value.

NOTE The PTO is likely to be of little sophistication. Often, an apparatus that provides a distinctive volume flow rate to pressure drop relationship is applied. This could be based on an orifice or thin (metal) tubes. The advantage of a stack of thin tubes is that low Reynolds number flows can be achieved. If the flow remains laminar, the pressure drop is readily calculated analytically (Hagen-Poiseuille flow).

9.3.3 Stage 2

The PTO control shall be capable of representing a realistic full-scale PTO control. As a minimum, the PTO characteristics shall be adjustable manually to offer different relations between the dynamic and kinematic sides of absorbed power. It is recommended to implement an adjustable damping characteristic, where the adjustment is undertaken through a control system.

One of the chosen PTO control modes shall be representative for the full-scale PTO control, and the similarity to the expected full-scale PTO control shall be quantified.

9.3.4 Stage 3

The degree of sophistication of the power conversion depends on the type of WEC under test and, in particular, the PCC. All devices shall include a control system, which shall be tested as part of the sea trial programme. The PTO control system shall include redundancy of essential sensors and control hardware.

Real-time measurement of the incident wave field is required to enable decision making on the type of trials to be run and the setting of the WEC systems. These shall be combined with real-time communication to the on-board control to adjust the system parameters as required by the test programme. A detailed log of the events shall be kept.

A supervisory control and data acquisition (SCADA) system shall be adopted for overall communication and control of the WEC during sea trials. This shall also undertake the data acquisition purpose, including telemetry requirements and on-board logging. The system shall have a meta-data function to ensure all files are time stamped and coded as specified in IEC TS 62600-100.

All sensors relevant for the power performance measurements shall connect via the SCADA.

A controller shall be incorporated into the SCADA for essential control of the operation of the WEC, especially the PTO setting.

9.4 Signal measurement

The purpose of the power performance measurements is to establish power performance of the WEC through measuring the relationship between the dynamics (PTO torque, force or pressure) and the kinematics (PTO angular velocity, velocity or flow rate). To achieve this, the measurements outlined in Table 8 shall be obtained. In Stages 1 and 2 power shall be measured after the first conversion stage, through the measured kinematics and dynamics. In Stage 3 power shall be measured at each conversion stage.

Table 8 – Power performance signal measurements

Signal measurements	Stage 1	Stage 2	Stage 3
Kinematics	All DoFs contributing to absorbed power	All DoFs contributing to absorbed power	All DoFs contributing to absorbed power at each conversion stage [†]
Dynamics	All DoFs contributing to absorbed power	All DoFs contributing to absorbed power	All DoFs contributing to absorbed power at each conversion stage [†]
Waves	Deploy at least 2 measurement probes during tests: one in front and one on the flanking side of the device.	Deploy at least 4 measurement probes during tests: in front, behind, and flanking each side of the device.	Deploy a measurement system within a justifiable distance ^{††} of the edge of the watch circle of the device
Current	Monitoring not required	Monitoring not required	Current shall be measured if this is expected to be predominant at site
Wind	Monitoring not required	Monitoring not required	Wind data from local weather station should be recorded
[†] After the primary power conversion step, the differentiation between kinematic and dynamic is lost. These are replaced by voltage and current and the electrical power can be measured directly. ^{††} A strongly varying bathymetry may justify closer measurement.			

All power performance signals shall be recorded on the same DAQ system (fully time synchronised) since multiplication between different quantities is required during the post processing.

If a control system is adopted, special consideration should be placed on the sample rates associated with real-time control. Typical real-time control loop rates are in excess of 1 kHz, and any associated input signal should be updated at a matching sample rate.

A real-time digital PTO control will require specialist hardware and software. Developing real-time control components is a challenging task, and it is recommended to subcontract this task to a specialist supplier, unless an experienced control engineer is part of the WEC development team.

9.5 Calibration and setup

Accurate calibration of the PTO arrangement is essential and shall be performed prior to experimental testing over the design frequency range to fully characterise the dynamic function of the PTO. The minimum set of calibration requirements are outlined in Table 9.

All sensors used in the experiments shall be statically pre-calibrated for their intended use. If a sensor is used in a dynamic environment, the time response and cross-coupling characteristics shall be investigated.

The representational PTO shall be exercised over the expected range of velocity, forces and frequencies (or equivalently pressures and flow rates). The theoretical dynamic and kinematic relationship should be compared to the empirical results to determine the acceptability. Plots of the PTO parameters will highlight the linearity of the response.

Table 9 – Power performance calibrations

Dry calibration	Stage 1	Stage 2	Stage 3
Physical model	CoG, locations and magnitudes of added ballast, moments of inertia	CoG, locations and magnitudes of added ballast, moments of inertia	CoG, locations and magnitudes of added ballast, moments of inertia
Wet calibration	Stage 1	Stage 2	Stage 3
Physical model	Floating position verification. Decay tests to determine natural period and damping in DoF used for power absorption	Floating position verification. Decay tests to determine natural period and damping in DoF used for power absorption	Floating position verification.
Wave sensors	Calibration of wave gauges shall be done frequently enough to ensure changes due to e.g. temperature changes are captured	Calibration of wave gauges shall be done frequently enough to ensure changes due to e.g. temperature changes are captured. Checks of non-linearity shall be undertaken	Wave buoy (or similar) transfer functions can be taken from buoy manufacturer

It is recommended to undertake the Stage 1 and Stage 2 decay tests with and without the mooring system in place. This will confirm the influence of the mooring system on the overall system dynamics.

9.6 Wave parameters

9.6.1 Stage 1 and 2

The minimum requirements for the laboratory (Stage 1 and 2) power performance tests shall follow those outlined in Table 10. Sea states shall be selected such that they adequately cover a representative scatter diagram.

Table 10 – Power performance wave parameters

Obtain power performance	Stage 1	Stage 2
Regular waves	10 periods per configuration of the device for 30 waves duration each. For selected configurations, the testing should be repeated with at least one additional wave amplitude	10 periods per configuration of the model for 30 waves duration each. For selected device configurations, the testing should be repeated with at least two other wave amplitudes.
Irregular long-crested waves at a nominal direction	5 operational sea states (for each tested spectral shape) of 250 waves duration each.	15 operational sea states (for each tested spectral shape) of 250 waves duration each.
Irregular short-crested sea states	Generally outside the scope of Stage 1 testing	3 directional sea states for 1 500 waves duration each

It is important to highlight that all requirements above are minimum requirements. Extended regular wave testing may often be beneficial for mathematical or numerical model development purposes.

Established sea states can be used, but site specific requirements shall be included in this evaluation where a potential device deployment site has been identified.

NOTE Sea states can be selected randomly across the scatter diagram, or it can be helpful to select iso-periods and iso-height (or iso-steepness) curves.

9.6.2 Stage 3

For sea trials, the test schedule shall be constructed such that changes to the device configuration, especially the PTO settings, can be compared across the encountered sea states. The purpose is to produce relative power matrices for each device setup. The actual bivariate scatter diagram element selected can vary but attention shall be paid to other parameters of importance such as spectral shape or wave direction since these two may influence the energy conversion process.

To accommodate sea state variability and complete Stage 3 satisfactorily, a robust test plan for a sufficiently extended time period shall be required.

9.7 Performance indicators

Variables of interest to achieve the goals are continuous in nature, hence for each performance indicator, the reporting outlined in 6.3 shall be adopted. Two key aspects shall be computed to meet the goals: absorbed power and PTO control characteristics.

The absorbed power $P(t)$ shall be based on the time series of two measured quantities, dynamics and kinematics (typically force and velocity, moment and rotational speed, or pressure and flow velocity), multiplied time step by time step. Often the kinematic side of the absorbed power is not measured directly and thus signal processing techniques shall be employed to derive this time series from a measured quantity. Each relevant DoF shall be processed according to 6.3.

The characteristics of the PTO control shall be reported. A scatter plot of the dynamic and kinematic quantities should be made to determine the characteristics of the PTO control.

NOTE In case of proportional damping PTO control, the points in the scatter plot will be at the diagonal and the corresponding damping coefficient is derived as the inclination of the diagonal.

For Stage 3 sea trials, the power conversion calculation shall be based on IEC TS 62600-100.

10 Kinematics and dynamics in operational environments

10.1 Testing goals

The purpose of this testing is to provide an indication of the device mooring loads, device motions, loading on the device structure, and seaworthiness (for example stability or down flooding). In Stage 1 the motions and predominant cross-sectional loads are investigated through the use of RAO curves. In Stage 2, local loads are investigated as needed as well as more comprehensive measurements of the WEC cross-sectional loads, motions, and mooring characteristics. These measurements can be placed in a bivariate scatter diagram to obtain estimates of these values on an annual basis. Lastly, in Stage 3 the loading (local, cross-sectional, and mooring) and motion characteristics of the WEC will be used to populate the bivariate scatter diagram.

The kinematics and dynamics testing in operational environments shall also provide sufficient data enabling definition of error bars for each of the relevant parameters (Annex D).

10.2 Testing similitude

With a progression in staged development, there should be a corresponding progression in the fidelity of the physical model; incorporating additional detail in the model design so a more definite design shall be used in Stage 2 over Stage 1. Supporting calculations shall identify likely failure points, and locations of high stresses, and the model shall be designed and manufactured to enable relevant strain or load measurements at these locations.

Table 11 defines the parameters that shall be adopted for geometric, structural, and PCC similitude for testing kinematics and dynamics in operational environments.

Often, the only physical system that is required to achieve structural similitude is the mooring system. Implementing catenary mooring systems at small scale is problematic as tanks are often too small to accommodate the footprint. Alternative configurations, for example using buoy and sinkers, should be considered. A simple spring mechanism can be adopted to ensure station keeping during early experimentation. In the case of active moorings (where the mooring plays an active role in wave power absorption), special attention shall be placed upon the mooring characterisation. In all cases, the mooring characteristics shall be verified experimentally.

The power conversion mechanisms set WEC testing apart from most other types of tank testing. Achieving PTO similitude often requires inventive and alternative configurations. Since the goal of this testing is not to understand the power production, achieving similitude is technically not required. However, since the kinematics and dynamics of a device are partially dictated by the operation of the PTO, a mechanism shall be implemented that achieves representative kinematics and dynamics.

NOTE Often power performance testing (Clause 9) is completed in concert with kinematics and dynamics in operational conditions (Clause 10) to obviate this issue.

The hydrodynamic similitudes set the scale of the environment and device to be tested, the scaled device parameters shall be matched as outlined in Table 6.

Table 11 – Kinematics and dynamics similitude requirements (operational environments)

Geometric similitude	Stage 1	Stage 2	Stage 3
WEC	Major properties of profile scaled to match the produced environment to within 15 %; constrained DoF testing allowed	Major properties of the profile scaled to match full-scale design to within 5 %	All dominant properties of the profile scaled to match full-scale design to within 3 %
Mooring	Full layout (footprint) not essential	Full layout (footprint) not essential	All dominant properties and scaled to match scaling parameter
Structural similitude	Stage 1	Stage 2	Stage 3
WEC	Not essential unless fundamental to power conversion	Not essential unless fundamental to power conversion	Where possible, match the full-scale materials and construction techniques, even if this will result in skewed scaling for the structural response
Mooring	Properties proportional to distance and scaled pre-tension scaled to match the produced environment to within 15 %	Properties proportional to distance and velocity; as well as the scaled pre-tension scaled to match full-scale design to within 5 %	All properties and scaled to match scaling parameter
PCC similitude	Stage 1	Stage 2	Stage 3
Drivetrain	A representative mechanism should be used that will result in the motions that should be characterised	A representative mechanism should be used that will result in the motions that should be characterised	Exact mechanical equivalent in type and scaled to match scaling parameter
Generator			Exact generator equivalent in type and scaled to match scaling parameter
Controls			Exact equivalent in operation

Typical Froude scale factors are of order 1:25 – 100 (Stage 1), 1:10 – 1:25 (Stage 2) and 1:2 – 5 (Stage 3). This will result in incorrect Reynolds scaling; if any special techniques are employed to alter the Reynolds regime, these should be documented. Annex C provides additional scaling guidance.

10.3 Signal measurement

Kinematic motions in each wave case shall be measured. A full six DoF motion tracking system is recommended. Six DoF tracking systems require calibration, and this shall be undertaken with assistance from the tank operator due to its complexity. The six DoF tracking is commonly based on optical (camera based) techniques, so that no physical interaction takes place between the motion tracking system and the physical model.

If the model kinematic sensing relies on single DoF sensors (laser displacement sensor or potentiometer based), then the motion cross-coupling between the various DoFs and the measured axes (for example the effect of roll on vertical translation) shall be well understood.

NOTE In the case of multi-axes accelerometers, the placement of the sensor(s) within the model affects the post-processing. The data post-processing required to determine the six degree of freedom motion from a set of multi-axes accelerometers is non-trivial.

Table 12 identifies the kinematic measurement on the model and its subsystems in each stage required to successfully determine the performance indicators.

Table 12 – Kinematic signal measurements (operational environments)

Kinematic measurements	Stage 1	Stage 2	Stage 3
WEC	All independent and active DoFs for all bodies monitored to result in a full-scale accuracy of 10 % of the major length parameter	All independent DoFs for all bodies monitored to result in a full-scale accuracy of 1 % of the major length parameter	Global location of WEC in ocean
Mooring	Independent monitoring not essential. The WEC kinematics can be helpful in identify the mooring kinematics	Recommended to monitor all attachment points of all legs (at optional buoyancy chamber, at anchor point) to result in a full-scale accuracy of 1 % of the major length parameter of the device	Mooring anchor points (continuous monitoring not obligatory, but regular checks on position highly recommended)
PTO	Not required	Not required	All DoFs contributing to absorbed power

Model movements should be accounted for when determining the range of the six DoF tracking system and the associated marker placement on the model where applicable.

Measurements capturing the forces, moments, and pressures (the dynamics) in each wave case shall be made. The choice of specific sensor should be determined based on:

- Maximum magnitude.
- Time resolution.
- Accuracy.
- Magnitude resolution.
- Weight (it should not influence the mass profile of the device being tested).
- Waterproofing (if required, the sensor shall be sealed against the ingress of fluid).

Sensors should be selected such that they deliver adequate accuracy and resolution for the expected signal magnitude.

It is recommended to measure local loads (pressures) on key components (see WEC: Local points in Table 13), particularly where the device is suspected to be susceptible to highly localised impacts like green water (water rising above the SWL and “sitting” on top of the device), slam event (device moving out of water and then re-entering, or highly localised fluid impacts), or other impacts that could occur due to motion limitations (like end-stops).

Forces and moments acting on the model at points of high stress concentration shall be recorded (see WEC: Cross-sectional loads in Table 13). There are fundamentally two types of stress that shall be characterised: Compressive or tensile stress parallel to the stress plane and shear stress perpendicular to the stress plane. Shear stress can either be characterised by measuring out-of-plane stresses or by measuring moments. The need to characterise these stresses depends upon the physical design of the device and the stage of testing. A structural engineer should be consulted to determine the primary points of stress concentration and their primary planes.

Table 13 identifies the required dynamic measurements on the model and its subsystems in each stage, required to successfully determine the performance indicators. Note that the determination of the requirements is often based on performance seen in earlier stages.

Table 13 – Dynamic signal measurements (operational environments)

Dynamic measurements	Stage 1	Stage 2	Stage 3
WEC: Local loads	Sensing not essential; however green water, slamming, and/or impact events are to be visually identified and noted in final report	Monitoring recommended if green water or slamming was seen in Stage 1. Monitoring required if other impact event occurred in Stage 1.	Monitoring required if greenwater or slamming was seen in Stage 2. Monitoring recommended if impact event occurred in Stage 2.
WEC: Cross-sectional loads	Cross-sectional loads should be sensed in primary stress plane.	Cross-sectional loads shall be measured in primary stress plane and shall be measured in out-of-plane directions (alternatively the bending moments may be measured)	Cross-sectional loads shall be measured in 3 DoF.
Mooring	Floating: line in predominant wave direction at attachment point to WEC to result in a full-scale accuracy of 20 % of the expected peak load Fixed: connection point in one DoF in a full-scale accuracy of 20 % of expected peak load	Floating: all lines (including umbilical when relevant) at attachment point to WEC to result in a full-scale accuracy of 5 % of the expected peak load Fixed: connection point in six DoF with a full-scale accuracy of 5 % of the expected peak load (special attention to be paid to cross-coupling)	Floating: all legs to result in a full-scale accuracy of 3 % of the expected peak load Fixed: connection point in six DoF with a full-scale accuracy of 3 % of the expected peak load (special attention to be paid to cross-coupling)
PTO	Not required	Not required	All DoFs contributing to absorbed power

To confirm that the dynamic measurement sensors did not undergo plastic deformations by surpassing their maximum magnitudes, the calibration shall be confirmed after the testing has taken place.

The environment shall be monitored as specified in Clause 7.

10.4 Calibration and setup

Model setup within the tank and the appropriate calibrations (both dry and wet) are key to ensuring accurate device response modelling.

All sensors used in the experiments shall be statically pre-calibrated for their intended use. If a sensor is used in a dynamic environment, the time response and cross-coupling characteristics shall be investigated

Table 14 shall be used to determine the minimum calibration requirements.

Table 14 – Calibration for kinematic and dynamic testing (operational environments)

Dry calibration	Stage 1	Stage 2	Stage 3
Physical model	CoG, Locations and magnitudes of added ballast, moments of inertia, location in the tank		
Mooring	The location of the connection point to the tank walls or floor of the tank as well as the length and type of line shall be recorded. Load cell statically calibrated in all DoFs	The location of the connection point to the tank walls or floor of the tank as well as the length and type of line shall be recorded. This load cell shall be calibrated in all DoFs, and cross-coupling between the DoFs shall be documented.	Load cell calibrated in all DoFs, and cross-coupling between the DoFs shall be documented
Wet calibration	Stage 1	Stage 2	Stage 3
Physical model	Natural periods, location in the water column	Natural periods in all DoF, location in the water, viscous damping, inclination tests to determine metacentric height	Natural periods in all DoF, location in the water column, viscous damping, inclination tests to determine metacentric height
WEC: Local loads	Not essential	A similar impact to that expected will be simulated in the tank to verify operation of sensor (i.e. a drop test for slamming)	Select sensor specification based on Stage 2 experience
WEC: Points of stress concentration	The primary plane should be excited with at least 3 known loads to verify operation.	Each relevant plane should be excited with at least 3 known loads to verify operation. Any cross-coupling should be noted and quantified.	Select sensor specification based on Stage 2 experience
Wave sensors	Calibration of wave gauges shall be done frequently enough to ensure changes due to e.g. temperature changes are captured	Calibration of wave gauges shall be done frequently enough to ensure changes due to e.g. temperature changes are captured. Checks of non-linearity shall be undertaken	Wave buoy (or similar) transfer functions can be taken from buoy manufacturer
Mooring	Floating: Produce mooring stiffness graph and adjust still water pre-tensions adjusted to meet expectations. Fixed: Operation of the load cell to be verified by exciting the cell with at least 3 known loads in each DoF.		

10.5 Wave parameters

10.5.1 Stages 1 and 2

The minimum requirements for the laboratory (Stages 1 and 2) dynamics and kinematics tests shall follow those outlined in Table 15. Sea states shall be selected such that they adequately cover a representative scatter diagram.

Table 15 – Wave parameters for kinematics and dynamics testing (operational conditions)

Obtain dynamics and kinematics	Stage 1	Stage 2
Regular waves	10 periods per configurations of the device for 50 waves duration each. For selected configurations, the testing should be repeated with at least one additional wave amplitude	10 periods per configurations of the model for 50 waves duration each. For selected device configurations, the testing should be repeated with at least two other wave amplitudes.
Irregular long-crested waves at a nominal direction	5 operational sea states (for each tested spectral shape) of 250 waves duration each.	15 operational sea states (for each tested spectral shape) of 250 waves duration each.
Irregular short-crested sea states	Generally outside the scope of Stage 1 testing	3 directional sea states for 1 500 waves duration each

It is important to highlight that all requirements above are minimum requirements. Extended regular wave testing may often be beneficial for mathematical or numerical model development purposes.

In Stage 2 a subset of the 15 operational waves should be determined according to the following guidance. Three constant steepness sweeps of three data points each should be employed when spanning the scatter diagram. One of these constant steepness sweeps should lie close to the facility's maximum wave generation capabilities. The other two constant steepness sweeps should attempt to span as much of the relevant scatter diagram as possible. This will leave 6 additional sea-states at the complete discretion of needs of the experiment.

NOTE The power is dependent on both the wave period and the wave height, and in deep water is given by $\rho g^2 / (64\pi) T_e H_{m0}^2$. Since the wavelength is found through the dispersion relationship which depends only on period and depth, when working along a constant steepness line (ratio of H_{m0} to λ_e), the power dependence collapses to period and steepness value only. By establishing three constant steepness curves, interpolation between the constant steepness lines is generally straightforward as all wave heights can be interpolated for a given period.

10.5.2 Stage 3

For sea trials, the test schedule shall be constructed such that changes to the device configuration, especially the PTO settings, can be compared across a statistically significant number of prevailing sea states. The purpose is to quantify the device behaviour for each device setup.

To accommodate sea state variability and complete Stage 3 satisfactorily a robust test plan for a sufficiently extended time period shall be required.

10.6 Performance indicators

Variables of interest to achieve the goals are both continuous and discrete in nature.

The characterisation of the response shall be based on the kinematic (WEC and mooring) and dynamic (WEC local loads, WEC cross-sectional loads and mooring loads) measurements as well as the environmental measurements. For each of these performance indicators, the reporting outlined in Clause 6 shall be adopted.

The characterisation of the discrete response shall be based on counting the number of slamming events, greenwater events, and impact events. For each of these performance indicators, the reporting outlined in Clause 6 shall be adopted.

Given that monitoring of a representative PTO is not required for this set of testing, performance indicators need not be presented. Subclause 6.3 identifies these values.

11 Kinematics and dynamics in survival environments

11.1 Testing goals

Long term survival is essential for the success of any WEC technology. Testing under extreme storm (survival) conditions shall rely on a statistical representation of the main performance indicators. Defining just which seas, or combination of waves, create the ULS is not obvious and thus shall require a broad scope of environmental conditions.

The magnitude of the ULS condition is dependent upon the devices response (motions and loads) to environmental forcing. Hence there are two aspects to achieving survivability: designing the devices response to the forcing and structural engineering solutions capable of withstanding the loads and motions. This testing shall provide statistically significant knowledge of the loads on the hull and mooring given a device's response to various incoming environments. If specific survival strategies, i.e. strategies to alter the device response to environmental forcing, are considered they shall be tested.

Due to the scale of the environments that shall be required, dedicated models designed specifically for survival conditions may be required. An additional element that shall be considered for these models is the electrical umbilical that transports power from the WEC to a substation.

NOTE If survivability testing is conducted at the same facility as operational tests, the water depth is likely to be inadequate, unless a moveable tank floor is provided or the water level in the tank is adjustable.

There are no specific requirements on the generation of the survival environment in Stage 1 to determine the kinematics and dynamics in survival environments; however, results from this stage shall be used to qualitatively select appropriate survival strategies. In Stage 2, local loads and WEC cross-sectional loads along with WEC motions and mooring loads are all used to characterise the device's peak responses using the appropriate probability density functions. In Stage 3, the naturally occurring environment will not only provide data to further characterise the device response similarly to Stage 2, but additionally will allow for characterisation of the construction and equipment selected.

11.2 Testing similitude

Table 16 defines the parameters that shall be adopted for geometric, structural, and PCC similitude for testing kinematics and dynamics in survival environments. Stage 2 contains the majority of similitude requirements that are unique from those presented in Table 11 since at this stage a full testing program to determine statistically significant probability density functions shall occur.

As stated above, due to the size of the survival environments, it is often required to produce models at Stage 2 that are Froude scaled 1:25-100. Given the role of mooring systems in these conditions, geometric and structural similitude shall be achieved in Stage 2. Further, structural similitude for the electrical umbilical shall be achieved so that the influences of the cable forces on the device motions can be captured in testing.

Table 16 – Kinematics and dynamics similitude requirements (survival environments)

Geometric similitude	Stage 1	Stage 2	Stage 3
WEC	Major properties of profile scaled to match the produced environment to within 15 %; constrained DoF testing allowed	Major properties of the profile scaled to match full-scale design to within 10 %	All dominant properties of the profile scaled to match full-scale design to within 3 %
Mooring	Full layout (footprint) not essential	Full layout (footprint) to match full-scale design to within 5 %	All dominant properties and scaled to match scaling parameter
Structural similitude	Stage 1	Stage 2	Stage 3
WEC	Not essential unless fundamental to power conversion	If determining local load generation, essential to match structural properties within the vicinity of the measurement	Where possible, match the full-scale materials and construction techniques, even if this will result in skewed scaling for the structural response
Mooring	Properties proportional to distance and scaled pre-tension scaled to match the produced environment to within 15 %	Full nonlinear behaviour to match full-scale design to within 10 %	Full nonlinear behaviour to match full-scale design to within 3 %
Electrical umbilical	Not required	Full nonlinear behaviour to match full-scale design to within 10 %	Full nonlinear behaviour to match full-scale design to within 3 %
PCC similitude	Stage 1	Stage 2	Stage 3
Drivetrain	A representative mechanism should be used that will result in the motions that should be characterised. Particular survival strategies may require active components here, if so, requirements to follow clause 10.	A representative mechanism should be used that will result in the motions that should be characterised. Particular survival strategies may require active components here, if so, requirements to follow clause 10.	Exact mechanical equivalent in type and scaled to match scaling parameter
Generator			Exact generator equivalent in type and scaled to match scaling parameter
Controls			Exact equivalent in operation

11.3 Signal measurements

For requirements regarding signal measurement please refer to 10.3 with the following additions.

Special attention shall be given to the size and weight of the sensors, as scaling requirements typically lead to small models, especially at Stage 2.

NOTE Fitting suitable sensors with sufficient accuracy and fidelity to the model, without significantly altering the response, can prove challenging. In practice, accuracy requirements might lead to a need of splitting up the testing, so that each set of tests can focus on a separate aspect at a time.

Special attention shall also be given to the risk of snap loads in moorings, impact pressures and forces, which are significantly more likely to occur in survival environments. Sufficient ranges, dynamic properties and sampling frequencies shall be used to ensure that such events are accurately captured.

11.4 Calibration and setup

For requirements regarding calibration and setup please refer to 10.4 with the following additions.

Special attention shall be given to the fact that motions in survival conditions are likely to be very large; it shall be assured that the motion tracking system is setup and calibrated for the necessary space. Similarly, the mooring system implementation shall ensure valid representation of a full scale system in all encountered survival conditions.

It is recommended that combined wave and current testing forms part of the survival programme. In the absence of site specific data, the waves and current can be run co-linear for head and quarter seas. If possible beam seas should also be investigated.

NOTE Since the current will be more recti-linear in nature, the two excitation forces (wave and current) may be at an angle of up to 90°.

Re-calibration of the wave conditions at the device deployment station is required using an estimated current in the range of 0,5 m/s to 1,0 m/s. Single point water surface elevation measurements will suffice for this calibration, for both long and short crested wave conditions.

If a specific deployment site is identified those conditions should be used. If an insignificant current is present, this combination of environmental loading can be excluded.

11.5 Wave parameters

11.5.1 Stage 1

Full storm conditions will not be possible for the small scale model in the Stage 1 facility so the maximum seas possible following the breaking line should be generated.

11.5.2 Stage 2

Defining just which seas, or combination of waves, create the ULS is not obvious and thus shall require a broad scope of environmental conditions in Stage 2. The parameters that shall be varied include: energy, spectral shape, heading, spreading, current and wind. The proposed deployment location shall be used to determine the long-crested 50-year return period sea-state and the heading of this sea state in accordance with IEC TS 62600-2.

Having defined the baseline storm conditions, the series of steps required to obtain additional sea states is as follows:

- Create deviations from the baseline storm conditions to include 2 deviations in heading, 2 deviations in spread, 2 deviations in spectral shape, and 2 deviations in energy.
- These deviations shall interrogate the device's response to as many unique conditions as possible.
- The deviation in heading should cover as close to 90° as possible.
- Deviations in spread should move from long-crested waves to a $\cos^{2s}$, with s of 3, spectral shape to a wide and finally to a bimodal spectrum with the equivalent single mode description.
- The deviations in energy should move off the peak of the return contour (the point of maximum H_s) by $\pm 30\%$.

This series of experiments will result in a total of 12 unique environments, each designed to test the sensitivity of the device's response to a unique aspect of a sea-state's potential variation. Since each parameter has a total of three tests (the baseline with two deviations) iso-variable trends of a considered device response can be obtained as mentioned in 6.2.5. These trends should indicate the sensitivity of the device's considered responses to alterations of the 50-year return period sea-state for the parameters tested.

Extreme environments are often nonlinear; hence accurate trends may not be resolved with only three data points. These recommendations should be expanded upon given a device's sensitivity and the need to obtain broader data for other purposes.

In addition to the above series, the device should be tested in a series of increasing energy along a constant steepness line. All parameters except energy shall be equivalent (heading, spread, and spectral shape), however, the energies along this constant steepness line should increase to at least twice the 50-year return contour. This will result in a series of 3 unique energies by which to evaluate and interpolate the device's response. This constant steepness testing should be an expansion upon the largest constant steepness sweep executed for the Stage 2 tests in Clause 10, thus providing three additional values by which to establish a trend. It is possible that those previous tests may have been performed for distinct sea-state parameters, and thus these distinctions should be noted and accounted for if possible.

The largest energy sea-state executed for the Stage 2 tests in Clause 10 shall be repeated matching exactly the sea-state parameters used in the Stage 2 tests in Clause 10.

Combining results from the operational environment with results from the survival environment is considered best practice and is hence recommended here. This practice allows for many important comparisons to occur (correcting for scaling): 1) the difference in results at the same measurement locations, 2) the difference in motions, 3) the effect of adding the umbilical, and 4) the influence of the true geometrically scaled mooring on the design. These comparisons may be possible both through the repeat sea-state but also through the inclusion of the data points into the constant steepness sweep.

Analysis of the device's response to the 12 sea-states tested above shall result in the determination of the extreme condition that the device shall derive the ULS from. Once this condition is determined, a last series of tests shall be performed to include the simulated effects of wind and current. The baseline wind and current conditions shall be determined for the site from historical data in accordance with IEC TS 62600-2. Three additional tests shall be conducted to determine the influence of these environmental parameters: wind and current collinear with heading, wind and heading collinear with current at unique heading, and lastly wind and current at a unique heading from the incident sea-state.

The duration of all 15 tests shall be such that statistically significant data are obtained, i.e. shall be generated to simulate 3 h storm conditions.

11.5.3 Stage 3

Before the Stage 3 sea trials have been completed, the WEC shall be exposed to extreme waves in high energy seas. A survival strategy shall be available, including the option to remove the device during such conditions.

Stage 3 survival testing is sought to achieve conditions that get close to true survival conditions. Example interpretations of such testing conditions include:

- a) testing that achieves 80 % of the expected ULS;
- b) testing that achieves the worst possible condition for a 1-year period at the Stage 3 deployment location, or
- c) an accelerated exposure of the device to high energy seas at a more exposed site with the proviso that destructive seas may also occur at such sites. Other interpretations are possible and are to be noted in the reporting.

11.6 Performance indicators

Variables of interest to achieve the goals are both continuous and discrete in nature.

The characterisation of the continuous response shall be based on the kinematic (WEC, location of mooring line seabed contact, if relevant any other mooring bodies kinematics, and the umbilical kinematics) and dynamic (WEC local loads, WEC cross-sectional loads, mooring loads, and umbilical loads) measurements as well as the environmental measurements. For each of these performance indicators, the reporting outlined in Clause 6 shall be adopted.

The characterisation of the discrete response shall be based on counting the number of slamming events, greenwater events, snap events in the mooring, and snap events in the umbilical.

The reporting requirements for the performance indicators in Clause 7 mainly focus on the full time history of data. In the case of obtaining relevant statistics for survival, the full time history is not primary, rather only the distribution of peak values which will follow a relevant distribution (Weibull, Gumbel, Gamma, etc.) that are of importance. These distributions will establish the quantile for the various performance indicators from which the ULS will be determined.

Given that monitoring of a representative PTO is not required for this set of testing, performance indicators need not be presented. Subclause 6.3 identifies these values.

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Annex A (informative)

Stage Gates

A.1 Overview

An essential part of the structured (TRL) development scheme is the continuous assessment and evaluation of how the device is performing relative to initial expectations and the prevailing industrial standards. The due diligence exercised defines the Stage Gate process and should combine the developers design statements and the uncertainty relevant to the appropriate Stage (TRL) of testing. At a minimum, the Stage Gates should be applied at the conclusion of each specific scale test programme, but additional evaluation, relevant to the goal-oriented trials, are recommended. It is also recommended that a 3rd party technical review is conducted on the evolving design to ensure the device can be engineered and will achieve certification status when at the prototype scale.

A.2 Design statements

As stated in Clause 5, at the beginning of the test programme, a design statement should be produced listing the expected behaviour and performance metrics for the device under development. As the testing progresses through the Stages, the specification for the device will become increasingly detailed and the uncertainties of the trial data will reduce.

The design statements should begin at TRL1, the theoretical evaluation of the concept, and continue into TRL2, the mathematical simulations section of the staged development programme. Although not part of the physical testing schedule, these TRLs are important since they encourage the device developers to consider a wider overview of a new device than just the energy conversion aspect of the design. It is not difficult to conceive a method of converting the wave hydrodynamic energy into a mechanical form from which electricity can be produced, but to do this safely and economically in real, directional seas, and survive storm conditions is not trivial. The design statement and appropriate Stage Gate criteria support the device developer to consider these important aspects of successful wave energy device design from the initial concept.

The basic rationale for the staged development process is to reduce the technical and financial risk of developing a wave energy device by investigating the appropriate device parameters at the suitable geometric scale. To achieve this, an increasing level of sophistication shall be incorporated in the test procedure as the device advances through the five Stages (9 TRLs), of which only the first three are covered in this TS. This ordered approach also reduces the uncertainty of the full-scale predictions in two ways. Firstly, by strategically applying more criteria into the Stage Gate evaluation and secondly by progressively increasing the physical size of the device model. As described in Annex D, prediction errors can also be reduced by increasingly improving the data monitoring and measuring quality during the advancing scale test schedule.

A.3 Stage Gate criteria

Stage 1 (TRL3): At the small-scale model (Stage 1), the design statement can be quite basic and the evaluation criteria restricted. Combined, these two specifications result in wide uncertainty of the analysed performance matrix results. Among others, construction methods, PTO manufacture, routine servicing and maintenance and deployment can be considered briefly. The primary Stage Gates, as described in 4.3, can concentrate on the behaviour and power conversion ability of the device in a selected number of wave conditions.