IEC TS 62600-103

Edition 2.0 2024-07
REDLINE VERSION

TECHNICAL SPECIFICATION

colour inside

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

IEC TS 62600-103:2024-07 RLV(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.140

ISBN 978-2-8322-9373-7

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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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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC TS 62600-103:2018. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

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

This second edition cancels and replaces the first edition published in 2018. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) Revised several numeric values (e.g. test durations) to align with best testing practice;
b) Introduced guidance and requirements relating to PTO testing and closed-loop control;
c) Introduced uncertainty clause in normative part of the document;
d) Strengthened the document sections relating to Stage 3, the first sea trials;
e) Updated the data synchronisation requirements to align with best testing practices.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
114/510/DTS	114/523/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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 webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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 document 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.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 Clause 2 and Clause 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 (Clause 9 to Clause 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), data acquisition and real-time control (Clause 8), and testing uncertainty Clause 12 are also included.

The structured development schedule makes use of the ability to accurately scale wave energy converters 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 wave energy converter'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 wave energy converters 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.

An essential element for any published Technical Specification or International Standard is to allow an opportunity to provide feedback on its contents to the appropriate TC 114 Working Group. TC 114 utilizes a standard methodology to allow this.

To submit feedback such as proposed changes, corrections and/or improvements to this document, please send an email to the TC 114 Chair using the Contact TC 114 Officers feature on the IEC TC 114 Dashboard, accessible at www.iec.ch/tc114. On the right side of the Dashboard under Further information select the link to contact the TC 114 Officers. On the subsequent page find and select the Send Email link for the Chair to access the email tool.

Complete all the required elements within the email pop-up. For the Subject field please include the document title and edition you are providing feedback for (ex: feedback for TS 62600-1 ED2). In the Message field, include text which summarizes your feedback and note if further information can be made available (note attachments are not allowed). The Chair may request added information as needed before forwarding the submission to the remaining TC 114 Officers for review and then to the appropriate Working Group for their consideration.

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 wave energy converters (WECs). It includes wave tank test programmes, where wave conditions are controlled so they can be scheduled, and 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.~~ Commercial-scale prototype tests are not covered in this document.

This document ~~describes~~ prescribes 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. Provided 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 defendable results of defined uncertainty.

This document serves 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: Marine energy systems – 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, symbols and abbreviated terms

3.1 Terms and definitions

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

~~**3.1.1**~~
~~**cross-sectional load**~~
~~compressive or tensile stress parallel to the stress plane and shear stress perpendicular to the stress plane~~

3.1.1
dynamic
forces responsible for the object's motion

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

3.1.2
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~~

3.1.3
operational sea states
wave conditions where the wave energy converter is in power production mode

~~**3.1.7**~~
~~**irregular wave**~~
~~wave composed of multiple frequency components~~

3.1.4
peak distribution
distribution of peak magnitude values

3.1.5
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.

3.1.6
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.

3.1.7
stage 3 <of wave energy converter testing>
~~large-scale~~ first 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~~

3.1.8
storm conditions <of a marine energy converter>
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 Symbols and abbreviated terms

For the purposes of this document, the following symbols and abbreviated terms apply.

g	Acceleration due to gravity	[m/s^2]
H	Wave height	[m]
H_{m0}	Significant wave height	[m]

J	Wave energy flux	[W/m]
P	Wave power	[W]
T	Wave period	[s]
T_e	Wave energy period	[s]
T_p	Wave peak period	[s]
T_z	Zero up-crossing period	[s]
λ	Length scale factor	[-]
θ	Wave direction	[rad]
ρ	Density	[kg/m^3]

AD	Analogue to digital
CoG	Centre of gravity
DAQ	Data acquisition as defined in IEC TS 62600-1
DFT	Discrete Fourier transform
DoF	Degree of freedom
FFT	Fast Fourier transform
FMECA	Failures mode, effects, and criticality analysis
IMU	Inertial measurement unit
OWC	Oscillating water column
PCC	Power conversion chain NOTE The power conversion chain is made up of a drivetrain, generator, storage, and power electronics.
PTO	Power take-off
RAO	Response amplitude operator
SCADA	Supervisory control and data acquisition system
SWL	Still water level
TRL	Technology readiness level
ULS	Ultimate limit state in the context of structural engineering
WEC	Wave energy converter

4 Staged development approach

4.1 General

Clause 4 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~~ commercial scale (or near ~~full~~ commercial 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 Clause 5 to Clause 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. The criteria are defined as a general framework and allow for a high degree of flexibility to suit the 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.

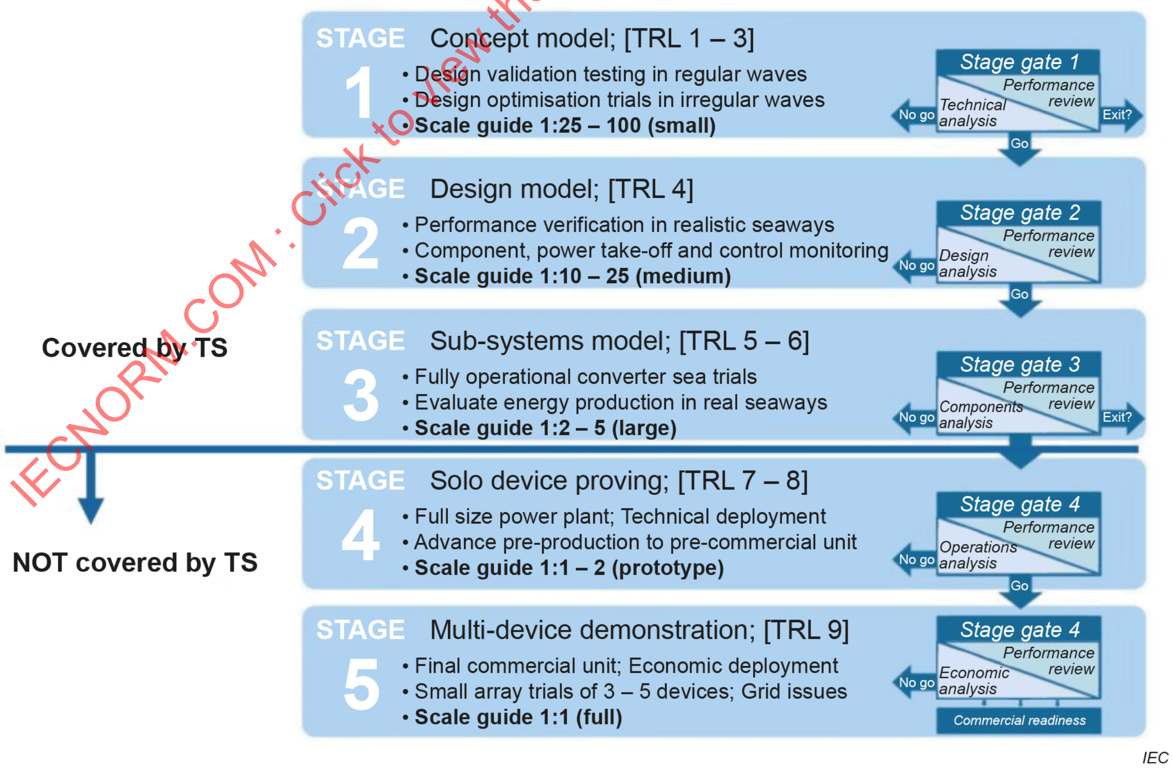


Figure 1 – Staged development approach

4.2 Stage gates

4.2.1 General

At the conclusion of each stage of device model testing, an evaluation procedure should be initiated 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 Clause 9, Clause 10 and Clause 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~~ data 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 specifications for each Stage Gate criterion that experimental testing can contribute to are outlined in Clause 9, Clause 10 and Clause 11 and summarised below.

Each stage can comprise more than one model testing campaign, using progressively optimised models, to maintain relevance as the device design progresses, and to comprehensively meet the Stage requirements and Stage Gate criteria.

NOTE Physical model testing is often run in conjunction with a mathematical model development, with model validation criteria similar to those listed in Clause 4.

4.3 Stage 1

4.3.1 Scope

Stage 1 is intended to demonstrate that the design has potential and ~~may~~ can 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 several device configurations without a detailed design for the ~~full~~ commercial 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~~ can 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~~ forcing 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 wave spectra distributions. This includes white or pink spectra for system identification purposes.

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

The methodology of testing recommended here follows established 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~~ commercial-scale design and data to be validated in the next stage.

4.3.2 Stage Gate 1

Energy absorption appraisal shall be based on:

- a set of power response transfer function (RAO, for similar wave heights);
- power capture prospects estimated ~~on a minimum of five~~ from selected sea states, with details provided in Clause 9.

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.

NOTE For a simple model with linear PTO damping, power absorption generally scales with the velocity squared, or the wave height squared. It can hence be beneficial to express the power response as a quadratic transfer function of form Power/Height^2, rather than an RAO that is of the form Power/Height.

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:

[1] Numbers in square brackets refer to the Bibliography.

- 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~~ commercial-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~~ extreme 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~~ model, exhibiting an accurate representation of the proposed ~~full~~ commercial-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~~ commercial-scale values with appropriate factors of safety. The data shall also (i) be suitable to confirm any mathematical or numerical models of the device where available; and (ii) be capable of extrapolation beyond one deployment location.

For validation of the Stage 1 results, both the wave and the device parameters ~~need to~~ should 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~~ settings) that supported the main Stage 1 conclusions. The medium-scale model ~~may have to~~ can 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:

- a power response transfer function (RAO, for similar wave heights);
- ~~power capture for a minimum of 15~~ power capture estimate based on a selected number of standard sea states (power matrix), with details given in Clause 9.

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~~ demonstrate in smaller scale the operating principles in “real world” uncontrolled wave conditions before ~~risking~~ building a ~~full~~ commercial scale prototype many times more expensive. 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 i.e. survivability.

There are several purposes for conducting testing at this stage, ranging from advanced technical and engineering issues, through to 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~~ materials 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~~ is likely to 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.~~ A grid emulator can substitute for connection to a grid.

The selected scale should strongly consider the overlap of wave heights and periods between the commercial site and the test site when appropriately scaled using Froude scaling. For sea-floor mounted devices, the scale of the model should preferably be chosen as the ratio between the water depth at the anticipated commercial site and the water depth at the test site. This recommendation is also advised, though less critical, for other WECs such that other systems (moorings, umbilical, etc) are representative.

The ~~test site and~~ scale should be ~~matched in moored depth, wave heights and periods and~~ used to scale any other parameters that affect the device and its subsystems. One issue can be the scaling of the water level variations and the local currents.

A comprehensive sea trial programme shall be developed for Stage 3 that provides sufficient confidence to move towards a ~~full~~ commercial-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 a well-defined set of trials will provide data as significant as ~~full~~ commercial scale but with a significantly reduced budget and technical risk.

NOTE Selecting an appropriate Stage 3 site is a challenging process, and the perfect site that suits all scaling and testing criteria might not exist. Some locations offer ideal water depth but not sufficient wave action, some locations meet the wave height criteria but do not scale well in terms of wave periods, and some locations provide the ideal wave climate, but only for very limited times during the year. To ensure that all testing objectives can be met, Stage 3 testing can be undertaken at more than a single location, where each location can meet part of the overall objectives.

4.5.2 Stage Gate 3

The Stage Gate in this case includes:

- the evaluation~~/~~ and verification of the PTO efficiency and control;
- the evaluation~~/~~ and verification of risk and safety management;
- the evaluation~~/~~ and 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;
- the evaluation of structural loads.

~~NOTE~~ Partial verifications are often undertaken before sea trials commence. For example, ~~it may be possible to evaluate~~ evaluating the PTO efficiency and control can be undertaken 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);
- PCC 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 PCC 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 to limit magnification of viscous forces that are not expected to be representative of full-scale effects.

NOTE 1 Inaccuracies ~~may~~ might be introduced through Reynolds, structural, and PCC 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~~ decreases.

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~~ can 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 frictional effects, like stiction, or non-physical hysteretic effects. Further, these representational PTOs may might 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 anticipated commercial-scale 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 commercial-scale approach 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.

a) 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 commercial 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.

b) 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 commercial scale and the experimental design at model scale;
- definition of the anticipated full commercial-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~~ commercial 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, significant wave height, spectral representation and directionality, spreading coefficient (see IEC TS 62600-101 for details);
- indicate the scale to be used on the above site conditions to fit the model tests at each scale (see Annex D Table D.1).

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.

c) 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, significant wave height, and if available spectral representation and directionality, spreading coefficient (see IEC TS 62600-101 for details). Additionally, an estimate of the anticipated deployment length ~~needed~~ required to sufficiently meet the testing goals;
- appropriate checks for scaling of operating sea states and extreme seas;
- appropriate checks for scaling of water depth, water level and currents;
- 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 Clause 9, Clause 10 and Clause 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 [4].

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~~ site selection:

- Appropriate spatial and temporal wave condition in both amplitude and period.
- Appropriate water depth for mooring fidelity.
- Sea bed conditions to suit mooring requirements.
- Local (rapid) changes in sea bed conditions that are likely to affect testing.
- Convenient launch and deployment facilities, and particularly vessel availability.
- Local service and maintenance amenities.
- Land-based data station.
- Appropriate atmospheric and oceanographic conditions, such as the absence of rip currents, large tidal variations, tidal races, 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, see 4.5.1 for details. 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~~ can be run by a State or private ~~concern~~ entity. 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~~ extreme conditions.

Stage 3 ~~survival~~ extreme testing is sought to achieve conditions that get close to true ~~survival~~ extreme conditions. Many interpretations of such testing conditions are possible and are to be noted in the reporting. Example interpretations 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~~ might 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
- Water level variations (or tidal range).

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

5.4 Physical model considerations: Absorbing body and mooring system

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 the end goal of the overall 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~~ commercial-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.~~
- The mooring system ~~will need to~~ shall 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~~ This Stage 3 device might be a significant model on the order of many tonnes and 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 it is not necessary for the scaled device ~~need not~~ to be grid connected and an alternative method of power dissipation, for example 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~~ load paths within the device structure.

- Accurate and complete assembly procedures.
- Instrumentation ~~needed~~ required to record required data streams including sensor redundancy.
- Supervisory control and data acquisition system (SCADA).
- Efficiencies in the PCC.
- Accurate mooring designs and assembly procedures.
- Safety of workers during commissioning, 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. A PTO simulation can initially be installed to validate and verify the system hydrodynamics.

The detailed Stage 3 WEC hull design and fabrication is commonly undertaken by a specialist marine contractor. Hull design and fabrication are not within the scope of this document, and reference should be made to the appropriate guidelines and standards for marine fabrication.

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

5.5 Physical model considerations: PTO and closed-loop control

NOTE Subclause 5.5 is written with closed-loop feedback control in mind. For devices that do not feature closed-loop feedback control, some of the requirements here only apply in part.

5.5.1 General

It is important to recognize that closed-loop absorption control for WECs introduces effects that are quite different from those in open-loop marine systems such as vessels. At the onset of the design process, a basic understanding of closed-loop control theory should be developed. This includes aspects of system design such as considering the modes of drivetrain resonance and how these might be excited via closed-loop feedback control.

The PTO strongly affects the device performance. In general, the PTO works by applying a force on the WEC that depends upon the WEC motion. A simple damper, for example, applies a force that is proportional to velocity. The force can be applied by a mechanical damper or by a sophisticated device that measures the velocity and generates a force by means of an actuator, which is commanded by a control system. In both cases, the dynamic behaviour of the coupled PTO-WEC system differs from the behaviour of the WEC when disconnected from the PTO. As a result, the developer should characterize the behaviour of the PTO to characterize its effects on the device once installed and deployed for tank testing or sea trials.

The implementation of a control system can dramatically improve power absorption performance or can, in the extreme case, destroy the device through instability. Therefore, for any device that uses feedback control, close attention shall be paid to the closed-loop dynamic properties of the controlled PTO.

NOTE Problems due to stability commonly arise when feedback controllers are implemented. These issues are often due to the PTO not being properly designed to execute the desired control system, for example not being able to apply the desired level of damping.

Tuning of mechanical power versus electrical power can lead to very different PTO optimization outcomes. Each Stage 1-3 testing campaign should clearly identify the PTO optimization objective, for example to maximize mechanical power or to maximize electrical power at a defined conversion step.

A PTO and control system will ultimately only function if all system components work in unison. This commonly includes the PTO hardware (actuators, gearboxes, hydraulic circuits etc.), the instrumentation feeding into any active control system, and the real-time control system hardware and software. The PTO design process should identify all critical PTO component, and how these can be reliably integrated into an overall system. The PTO hardware (e.g. actuators) is likely very different between Stages 1 and 2, and Stage 3. The PTO characterization shall be repeated each time the PTO hardware changes substantially.

5.5.2 PTO and control design considerations for Stages 1 and 2

During a Stage 1 program, the PTO can be represented using a simplified, yet well-characterized mechanism.

During a Stage 2 program, the PTO shall be represented using a mechanism capable of exhibiting the proposed (or intended) commercial-scale kinematic and dynamic PTO characteristics and control strategy. If the commercial-scale or Stage 3 device relies on a closed loop feedback controller, then a closed loop feedback controller is also recommended during the Stage 2 model testing.

NOTE 1 The detailed design of the first sea-going (Stage 3) device often takes place following the Stage 2 model testing. As a result, either the Stage 3 or the commercial-scale PTO hardware, or both, might not be fully defined during the Stage 2 testing. Nevertheless, having a proposed or intended PTO concept in mind prior to Stage 2 model testing is key for the success of the overall staged testing approach, such that the intended kinematic and dynamic PTO characteristics can be tested during Stage 2.

NOTE 2 Matching the kinematic and dynamic behaviour is particularly important if the PTO at commercial scale is capable of providing significant amounts of reactive power. In this case, the motion of the WEC will be amplified by the interaction with the controlled PTO, and the wave-body response can be significantly different from the case where no PTO is included.

5.5.3 PTO and control design considerations for Stage 3

During a Stage 3 program, the PTO shall be represented using a mechanism capable of exhibiting the proposed commercial-scale kinematic and dynamic PTO characteristics and control strategy. If the commercial-scale device relies on a closed loop feedback controller, then a closed loop feedback controller shall also be tested during the Stage 3 sea trials.

The device power can be measured at various conversion steps, for example mechanical input power, and reported at those points. For each reported power performance value, it shall be documented exactly where in the PCC this power is recorded.

NOTE While peak power ratings for Stage 3 can be several kWs, continuous power flow in many sea states is likely of the order of several hundred Watts. As a result, efficient electrical power conversion (and potential transmission to shore) can be very challenging.

Stage 3 is the first stage that involves open water sea trials. The Supervisory Control and Data Acquisition System (SCADA) shall be designed such that it can handle autonomous operation of the WEC. The SCADA system can rely on manual intervention for certain tasks (e.g. switching between various control strategies) but shall be designed such that safety and seakeeping critical features do not rely on real-time operator input. The SCADA system 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 system.

5.5.4 PTO bench testing

Bench testing time is significantly less expensive than wave tank testing time (Stages 1 and 2) or sea trials (Stage 3). The key purpose of a PTO bench test is to identify the main issues and faults with the PTO design, such that the PTO integrated with the device is pre-tested and reliable [5]. This can greatly reduce the likelihood of failure of a wave tank or at sea testing.

There are two main types or purposes of PTO and control bench tests:

a) Characterize, verify, and validate an open-loop model of the PTO: This is useful for both the design of the controller and evaluation of performance and efficiency. With regards to control design, the model derived from experimental testing is useful also to establish the bounds on the controller performance (type of controller and range of stability margins);

b) Test control system: Verify closed-loop PTO behaviour before tank testing or sea trials.

It is recommended to undertake the first type, (a) above, for Stages 1 and 2. The second type, (b) above, should be undertaken for Stage 2.

Both (a) and (b) above shall be undertaken for Stage 3. The Stage 3 PTO is the first larger PTO assembly for most WEC developers, likely with actuators capable of delivering and accepting several kWs of power. Bench testing of the PTO drive train shall be undertaken prior to integrating the PTO within the Stage 3 WEC model. During this bench testing, the Stage 3 PTO drive train is likely to exhibit some unique behaviour (e.g. drive train resonances) that cannot be scaled to a commercial-scale device. Nevertheless, any such (resonant) behaviour should be documented to inform the commercial-scale device design.

NOTE It can be challenging to find a bench test laboratory for every type of Stage 3 PTO. For some shoreline OWC devices, sometimes the WEC system itself is the test bench for the PTO system.

Bench testing of PTO components can be undertaken using simplified device models, such as simple mass-spring-damper systems. Components of the real physical system can also be simulated using hardware-in-the-loop techniques. The key to bench testing is that the PTO hardware and control system are shown to be operating with good stability margins before being integrated into the WEC model for wave tank testing or sea trials.

During Stage 3 bench testing, the principal PTO control algorithms shall be tested as intended for the Stage 3 sea trials. This shall include executing those algorithms on the intended sea trial computing hardware (SCADA system). It is acceptable that not all physical sensors are present during the bench testing phase, and sensor signals can be simulated as required.

It is recommended that the PTO test stand is capable of compliant PTO excitation. In this context, compliant refers to the ability of the PTO test stand to react to the PTO forcing, rather than rigidly enforcing a motion profile that is not representative of the coupled interactions between the PTO and the wider WEC system.

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~~ commercial-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 either model or full-scale values, or both, 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 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 1 It is often helpful to also present subsets of the raw data time series.

NOTE 2 In calculating error bars, the uncertainty analysis in [6] can be helpful.

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. Clause 9 provides details concerning the number of regular waves to be considered. Error bars should be associated with both the abscissa and ordinate axes. The appropriate uncertainty analysis (see Clause 12) 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, 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 bivariate 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~~ can 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~~ can contain entries relating to a number of control settings.

For Stage 3 sea trails, it ~~may~~ might 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 should be associated with both the abscissa and the ordinate axes.

NOTE In calculating error bars, the uncertainty analysis in [6] can be helpful.

6.2.5.2 Capture width and capture width ratio

The capture widths for the individual tests shall be calculated based on 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.~~ Either the capture widths or capture width ratios, or both, shall be plotted against peak period of the spectrum. The measured model scale data should be presented. Predictions for commercial scale can be included. Typically the sea state over a test interval of 20 minutes will be given by the significant wave height estimate H_{m0} and wave energy period T_{e}.

NOTE These calculations can be presented at ~~prototype~~ commercial scale or in terms of non-dimensional parameters, e.g. wave steepness, H_{m0}/T_{e}, and relative length l, characteristic device length λ_{e} normalised by wave length (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 ~~/~~and 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 of 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 ± Std. Dev. <Peak> ± Std. Dev.	Average ± Std. Dev. <Peak> ± Std. Dev. <Phase of Peak> ± Std. Dev. <Peak> to Average ± 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 of performance indicators in irregular long-crested waves

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 waves. 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 ± Std. Dev. <Peak> ± Std. Dev. Peak	Average ± Std. Dev. <Peak> ± Std. Dev. <Peak> to Average ± Std. Dev. *Spectral response*: indicate the moments of the spectrum *Peak distribution:* 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~~ can 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 ± Std. Dev. <Peak> ± Std. Dev. Directional spectral response *Peak distribution:* identify 98th percentile	Average ± Std. Dev. <Peak> ± Std. Dev. Directional spectral response *Peak distribution:* 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:

a) calibration of the incident waves undertaken in the absence of the structure;

b) 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;

c) 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 [7]).

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 minimum required measurements for each aspect or type of the incident environment. Additional wave probes are recommended if the incident and reflected waves from the device are to be separated.

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 3 measurements during tests: in front, behind, and flanking one side of the device.	N/A
Wave	Irregular long-crested waves	Deploy at least 2 measurements during tests: in front and one flanking side of the device.	Deploy at least 3 measurements during tests: in front, behind, and flanking one side of the device.	N/A
Wave	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 50 m 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~~ can 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~~ should 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 the water surface elevation (wave elevation recorded at the surface), and calibration of the water surface elevation only ~~may~~ might 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 [8]. 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, either time or frequency domain analyses, or both, 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 [9]. 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 [10]. 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 [11]. 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 diagram 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, ± Std. Dev. Wave period T, ± Std. Dev. Wave direction θ, ± Std. Dev.		N/A
	Irregular long-crested waves	Significant wave height, H_{m0} 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 document refers to the methods established for open-sea characterisation in IEC TS 62600-101.

8 Data acquisition and real-time control system

8.1 Signal conditioning

Data acquisition is a rapidly evolving field, and this clause only serves as a brief overview. If in doubt, an experienced instrumentation engineer or the test facility should be consulted.

Modern DAQ systems often rely on distributed fieldbus protocols, where the analogue signal can readily be converted to a digital signal close to the signal source. Distributed fieldbus systems avoid issues with long analogue cable runs and associated noise and are hence recommended where possible. Where long analogue cable runs cannot be avoided, current loops (typically 4 mA to 20 mA) are recommended, or alternatively, sensors with analogue voltage outputs should be calibrated with the cable length included.

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:

a) The sensor lead should be kept as short ~~(0,5 m to 2 m)~~ as possible and the analogue to digital (AD) conversion should be undertaken in close spatial proximity to the sensor.

b) An instrumentation amplifier should be placed as close as possible to the sensor, providing a more robust electrical 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~~ . This can rely on techniques such as twisted and shielded pairs of wires ~~and/~~, or ~~use of~~ measuring methods employing long cable compensation (e.g. 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~~ might need to be corrected for these factors. Thus, these additional factors ~~would need to~~ shall 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.~~

It is recommended to discuss EMI noise mitigation measures on instrumentation signals with the testing facility. For example, shielded cable is recommended for analogue signals runs with the cable shield connected to the DAQ ground on the DAQ end.

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.

If signals are required for real-time feedback control (e.g. force or torque feedback), they should be recorded sufficiently fast to minimize control phase delays. For Stages 1 and 2, feedback control signals should be acquired at no less than 500 Hz. For Stage 3, feedback control signals should be acquired at no less than 200 Hz.

NOTE The appropriate data acquisition rate ~~may~~ can 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 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.~~

All signals should be recorded and synchronised on a common time base. This can be achieved by using the same DAQ system, although care should be taken that signal pre-conditioning does not introduce an excessive phase lag. Where implementing a common time base from a master clock (e.g. GPS time stamps) is not practical (e.g. due to hardware limitations) a common start trigger shall be used for synchronisation. In this case, a means of quantifying clock drift should be incorporated, such as a common periodic signal (e.g. sine wave) recorded on the individual DAQ systems.

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~~ might misalign samples. This should be checked during testing ~~and evolve~~ to obtain 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.
- PTO control settings.
- 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.
- A descriptive identifier associated with any model change, e.g. mooring angle, mooring spring stiffness, etc.

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 calibration factor is the relationship between the recorded signal unit (for example voltage) and the actual physical ~~property (the Calibration factors)~~ quantity (for example force) ~~shall be documented~~. Calibration factors for all sensors shall be documented.

8.9 Instrument response functions

In special cases, instrument response functions or compensation factors of non-ideal test conditions ~~may~~ might 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 ~~/~~or 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.

It is recommended to rely on industrial grade, off-the-shelf hardware for the WEC SCADA system. Such systems are readily available and enable deterministic control and data acquisition. Low-latency, low-jitter real-time digital fieldbus communication for control and feedback signals is recommended wherever possible.

NOTE Control theory and control algorithms might not have changed substantially in recent decades, but the way in which they are computed has. Digital real-time control on industrial grade computing systems is now industry best practice for new designs.

The control algorithm for power absorption control commonly only represents a small fraction of the code implementation required for the overall SCADA system. It is recommended to commence the design process for (i) the overall safety system; (ii) any required state machines, and (iii) control of auxiliary systems (e.g. fans, cooling circuits, load management system) well-ahead of the ocean deployment. It is also recommended to test any auxiliary system controls as part of the Stage 3 bench testing process in addition to the PTO bench testing outlined in 5.5.4.

The safety control system for a Stage 3 device is likely complex, and it is recommended to undertake a Failure Mode and Effect Analysis to aid the development of the safety system. The system should be fault tolerant, such that the overall control system is not susceptible to a single point of failure.

Once all controls (absorption controller, safety controls, auxiliary controls) have been integrated into a single system, their overall real-time computation might be significantly more burdensome on the computing hardware from when they operated in isolation during testing. It is hence recommended to undertake the control system integration as early as possible, and to allow sufficient computing headroom on the real-time control platform.

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 dimensions (length, width, etc.) of the WEC profile to approximate commercial-scale design. Constrained DoF testing allowed.	~~Major properties of the profile scaled to match full-scale design to within 5 %~~ Major dimensions (length, width, etc.) of the WEC profile to match commercial-scale design as closely as possible.	~~All properties of the profile scaled to match full-scale design within 3 %~~ All aspects of the WEC profile to match commercial-scale design as closely as possible.
Mooring	Full layout (footprint) not essential.	The principle of the mooring to WEC interface should be similar, while the similitude of the full layout (footprint) is not essential.	All dominant properties required and scaled to match ~~prototype~~ commercial-scale 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~~commercial-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 %~~ approximate commercial-scale design.	Properties proportional to distances, and scaled pre-tension scaled to match ~~the produced environment to within 5 %~~ commercial-scale design as closely as possible.	~~All dominant properties relevant and scaled to match scaling parameter~~ All relevant dominant properties scaled to match commercial-scale design as closely as possible.

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.	A mechanism should be used that will result in a representative and fully modellable response.	Exact mechanical equivalent in type and scaled to match prototype parameter.
Generator	PTO implementation: friction based or linear with velocity. Quadratic if an orifice plate is used.	PTO implementation: Friction based, linear or non-linear with velocity or PI, PID, MPC.	Exact generator equivalent in type and scaled to match ~~prototype parameter~~ commercial scale parameters.
Controls	Simplified controls; Coulomb or linear damping.	Controls equivalent in operation; however, aspects relating to time within the algorithms ~~may~~ might 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 (1:30 scale) to 0,1 W (1:100 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~~ commercial-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 though a control system.

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

See 4.5 for additional Stage 3 PTO and control system requirements.

9.4 ~~Signal~~ Physical measurements

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~~ physical 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[a].
Dynamics	All DoFs contributing to absorbed power.	All DoFs contributing to absorbed power.	All DoFs contributing to absorbed power at each conversion stage[a].
~~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~~

[a] 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.~~

Since multiplication between different quantities is required during the post processing, all power performance signals shall be recorded such that they can be fully time synchronised.

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 Stages 1 and 2

The minimum requirements for the laboratory (Stages 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. If the device performance is highly dependent on wave directionality, the Stage 2 testing is recommended to include directional sea states in addition to those noted in Table 10.

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~~ 1 h commercial-scale equivalent each.	15 operational sea states (for each tested spectral shape) of ~~250 waves duration~~ 1 h commercial-scale equivalent each.
Irregular short-crested sea states	Generally outside the scope of Stage 1 testing.	3 directional sea states ~~for 1 500 waves duration~~ of 3 h commercial-scale equivalent each.

It is important to highlight that all requirements above are minimum requirements. Extended regular wave testing ~~may~~ can 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~~ might 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 using RAO curves. In Stage 2, local loads are investigated as ~~needed~~ necessary, 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 dimensions (length, width, etc.) of the WEC profile to approximate commercial-scale design; constrained DoF testing allowed.	~~Major properties of the profile scaled to match full-scale design to within 5 %~~ Major dimensions (length, width, etc.) of the WEC profile to match commercial-scale design as closely as possible.	~~All dominant properties of the profile scaled to match full-scale design to within 3 %~~ All aspects of the WEC profile to match commercial-scale design as closely as possible.
Mooring	Full layout (footprint) not essential.	The principle of the mooring to WEC interface should be similar, while the similitude of the full layout (footprint) is 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~~ commercial-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 %~~ approximate the commercial-scale design.	Properties proportional to distance and velocity; as well as the scaled pre-tension scaled to match ~~full~~ commercial-scale design ~~to within 5 %~~ as closely as possible.	~~All properties and scaled to match scaling parameter~~ All relevant dominant properties scaled to match commercial-scale design as closely as possible.
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 – 1:100 (Stage 1), 1:10 – 1:25 (Stage 2) and 1:2 – 1:5 (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 addition scaling guidance.

10.3 ~~Signal~~ Physical measurements

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~~ physical 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 shall be monitored as accurately as possible. A less accurate measurement system (e.g. gyro or accelerometer) is permissible.	~~All independent DoFs for all bodies monitored to result in a full-scale accuracy of 1 % of the major length parameter~~ All independent DoFs for all bodies shall be monitored as accurately as possible. A more accurate measurement system (e.g. motion tracking) is recommended.	Global location of WEC in ocean.
Mooring	Independent monitoring not essential. The WEC kinematics can be helpful to 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~~ as accurately as possible.	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~~ loads in Table 13), particularly where the device is suspected to be susceptive 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~~ physical 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~~ are recommended to be sensed in primary stress plane.	Cross-sectional loads ~~shall~~ are recommended to be measured in primary stress plane and shall be measured in out-of-plane directions (alternatively the bending moments ~~may can~~ 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~~ be measured approximately based on the expected peak load. Fixed: connection point in one DoF ~~in a full-scale accuracy of 20 % of~~ to be measured approximately based on the 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~~ be measured as closely as possible to the expected peak load. Fixed: connection point in six DoF ~~with a full-scale accuracy of 5 % of~~ to be measured as closely as possible to 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~~ All legs to be measured as closely as possible to the expected peak load. Fixed: connection point in six DoF ~~with a full-scale accuracy of 3 % of~~ to be measured as closely as possible to 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~~ 30 waves duration each. For selected device configurations, the testing should be repeated with at least one additional wave ~~amplitude~~ height.	~~10~~ 15 periods per configurations of the ~~model~~ device for ~~50~~ 30 waves duration each. For selected device configurations, the testing should be repeated with at least two other wave ~~amplitudes~~ heights.
Irregular long-crested waves at a nominal direction	5 operational sea states (for each tested spectral shape) of ~~250 waves duration~~ 1 h commercial-scale equivalent each.	15 operational sea states (for each tested spectral shape) of ~~250 waves duration~~ 1 h commercial-scale equivalent each.
Irregular short-crested sea states	Generally outside the scope of Stage 1 testing.	3 directional sea states for ~~1 500 waves duration~~ 3 h commercial-scale equivalent each.

It is important to highlight that all requirements above are minimum requirements. Devices that are multi-modal might require additional testing to adequately define the device performance. Extended regular wave testing ~~may~~ can 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)~~ wavelength associated with T_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:

- kinematic measurements: WEC and mooring;
- dynamic measurements: WEC local load, WEC cross-sectional load (where specifically required) and mooring load;
- 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;
- 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, it is not necessary to present performance indicators; 6.3 identifies these values.

11 Kinematics and dynamics in ~~survival~~ extreme 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 device's 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~~ are required, dedicated models designed specifically for ~~survival~~ extreme conditions ~~may~~ might be required. These dedicated models can be at a smaller scale than the performance model, in order for the tank facility to be able to replicate the desired range of extreme environmental conditions. 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~~ extreme 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~~ extreme environment in Stage 1 to determine the kinematics and dynamics in ~~survival~~ extreme 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~~ extreme 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~~ extreme environments, it is often required to produce models at Stage 2 that are Froude scaled 1:25 – 1:100. 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~~ extreme 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 dimensions (length, width, etc.) of the WEC profile to approximate commercial-scale design; constrained DoF testing allowed.	~~Major properties of the profile scaled to match full-scale design to within 10 %~~ Major dimensions (length, width, etc.) of the WEC profile to match commercial-scale design as closely as possible.	~~All dominant properties of the profile scaled to match full-scale design to within 3 %~~ All aspects of the WEC profile to match commercial-scale design as closely as possible.
Mooring	Full layout (footprint) not essential.	Full layout (footprint) to match ~~full~~ commercial-scale design ~~to within 5 %~~ as closely as possible.	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~~ commercial-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 %~~ approximate commercial-scale design.	Full nonlinear behaviour to match ~~full~~ commercial-scale design ~~to within 10 %~~ as closely as possible.	Full nonlinear behaviour to match ~~full~~ commercial-scale design ~~to within 3 %~~ as closely as possible.
Electrical umbilical	Not required.	Full nonlinear behaviour to match ~~full~~ commercial-scale design ~~to within 10 %~~ as closely as possible.	Full nonlinear behaviour to match ~~full~~ commercial-scale design ~~to within 3 %~~ as closely as possible.
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~~ might require active components here, if so, requirements to follow Clause 9.	A representative mechanism should be used that will result in the motions that should be characterised. Particular survival strategies ~~may~~ might require active components here, if so, requirements to follow Clause 9.	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~~ Physical measurements

For requirements regarding ~~signal~~ physical measurements 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 necessitate a 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~~ extreme 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~~ extreme 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~~ commercial-scale system in all encountered ~~survival~~ extreme conditions.

It is recommended that combined wave and current testing forms part of the ~~survival~~ extremes testing 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 rectilinear in nature, the two excitation forces (wave and current) ~~may~~ might 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~~ might 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.

NOTE The key purpose of the Stage 1 extreme testing is to obtain a first indication of the seaworthiness of the device, for example if the device is susceptible to capsizing.

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~~ H_{m0}) by ± 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~~ might 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~~ extreme 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. Such comparisons ~~may be~~ are made 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 equivalent 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~~ extreme testing is sought to achieve conditions that get close to true ~~survival~~ extreme 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~~ might 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:

- kinematic measurements: WEC, location of mooring line seabed contact, if relevant any other mooring bodies kinematics, and the umbilical kinematics;
- dynamic measurements: WEC local loads, WEC cross-sectional loads(where specifically required), mooring loads, and umbilical loads;
- 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;
- snap events in the umbilical.

The reporting requirements for the performance indicators in Clause 6 mainly focus on the full time history of data. In the case of obtaining relevant statistics for ~~survival~~ extreme conditions, 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, it is not necessary to present performance indicators; 6.3 identifies these values.

12 Uncertainty

12.1 General

Minimizing and quantifying the uncertainty associated with any model testing experiment is undoubtably key. However, the magnitude of what can be considered an accepted uncertainty strongly depends on the context of the experimental data. If, for example, an experiment is undertaken in a highly mature field such as propulsion or vessel drag, only a few percent in performance improvements over the state-of-the-art can make the difference between success and failure of an experiment.

In the wave energy field, many of the Stage 1 to Stage 3 testing campaigns seek to introduce novel design concepts, rather than making incremental improvements over a baseline design. As a result, a higher level of uncertainty than in other, more mature, fields can be acceptable.

While good experimental practices remain key to low uncertainty, lower uncertainty is also often associated with higher campaign costs. For example, repeats of experiments cost basin time. Purchasing a 0,1 % accuracy force gauge would be more costly than a 1 % accuracy gauge of otherwise similar construction. A balance should be struck between (a) the ultimate objectives the experiments will satisfy; (b) acceptable uncertainty, and (c) cost.

12.2 Main sources of uncertainty

12.2.1 General

The scaled development programme described in this document is structured to de-risk the extensive process of engineering a wave energy converter from concept to commercial deployment. However, there are still several basic sources of uncertainty encountered at each of the stages of the testing:

- The variability of measured physical properties during testing (12.2.2);
- The differences between the realised tank model and the ideal designed commercial scale device (12.2.3);
- The inability to scale all physical properties within one of the standard similitude approaches (12.2.4);
- Procedural difference between testing facilities, for example the way in which wave fields are calibrated or characterized (12.2.5).

12.2.2 Variability of measured physical properties including control signals

Measurement uncertainty of physical properties is encountered in all fields of science, and hence not extensively covered in this document.

NOTE Methods to quantify typical measurement errors are well described in several publications including [6], [12], [13], [14] and [15].

Wave energy testing for Stages 1 and 2 is most commonly undertaken in established hydrodynamics laboratories. It is recommended that WEC technology developers consult with the facility staff in the selection of sensors and actuators, as well as the sensor and actuator wiring. Quality instrumentation and actuator control is highly experience based. It is recommended that experienced instrumentation and control engineers review the physical model setup prior to Stages 1 and 2 testing.

At Stage 3, the risk and consequences of failure are significantly higher. A single poorly terminated wire (e.g. for a feedback signal) or a single signal sign inversion in a feedback loop can lead to device destruction. To lower both risk of failure and uncertainty, experienced instrumentation and control engineers shall review the physical model setup prior to deployment at sea. It is recommended to work alongside experienced instrumentation and control engineers throughout the Stage 3 WEC development process.

12.2.3 Differences between model built and expected full-scale device

For model tests at Stages 2 and 3, the model design and built shall be representative of the planned commercial-scale device, with details provided in 5.4 and 5.5. This is less relevant at Stage 1, as the definition of the commercial-scale device might still be very conceptual.

In practice, particularly the Stage 2 model realisation that faithfully represents the anticipated full-scale device characteristics can be difficult to implement, as the material used and the space available for ballasting might vary, and the technology used for the PCC will, in most cases, be different. Some variations of the dynamic characteristics between the designed commercial-scale device and the realised Stage 2 model are therefore expected. These differences shall be documented and their potential impact on the device behaviour should be described to facilitate the interpretation of the results.

Adoption of model test results at a later stage in the development process shall take into account the potential variation on the design of the commercial scale device since the completion of the model tests, as well as an assessment of the uncertainty due to these variations.

12.2.4 Scale effects and device scale

For most wave energy model tests, Froude scaling is by far the most important scaling method. However, Reynolds scaling might also be relevant, for example if air flow through a turbine or duct is part of the WEC operating principle. Scaling similitude for wave energy testing is covered in Clause C.1.

Due to scale effects (see Clause C.1), errors will be introduced when up-scaling the experimental data. This source of uncertainty is the basis of increasing the physical model size to the largest size suitable for each stage. Figure 1 indicates 1:25 – 1:100 (Stage 1), 1:10 – 1:25 (Stage 2) and 1:2 – 1:5 (Stage 3) as approximate scales. However, no exact model scale recommendation can be provided, as the optimum scale strongly depends on the commercial-scale device size and the device design.

For Stages 1 and 2 it is recommended to design each model as large as can reasonably be accommodated by the testing facility. Material cost is unlikely to be a large contributing factor during Stages 1 and 2, and campaign cost will be dominated by staff time and testing facility costs.

NOTE 1 For small physical models, with only a few tens of Newtons of excitation forcing, instrumentation and control become increasingly challenging if not impractical. Friction between moving components and other auxiliary forcing effects become difficult to distinguish from the (desired) hydrodynamic forces. While very small models can seem attractive from a handling and material cost perspective, the extra time effort required for instrumentation and control can more than offset the savings in other areas of model fabrication.

Material and fabrication costs at Stage 3, including anchors, moorings, structural components, and PTO equipment, can be significant. For Stage 3, it is recommended to build at a scale of approximately 1:2 – 1:5, bearing in mind that the model shall be large enough to accommodate the physical PTO hardware.

NOTE 2 The Stage 3 scale can sometimes be dictated by the availability of off-the-shelf components. For many Stage 3 campaigns, custom components (for example, a custom wound high-torque motor) can prove cost prohibitive for a single prototype fabrication.

12.2.5 Procedural effects

Many errors and inconsistencies driving uncertainty in WEC model testing are procedural, rather than due to sensors or actuator accuracies.

The methods relating to sea state definition can differ between testing facilities. This can be overcome through exact sea state definition and sea state calibration. However, in many cases accurate sea state calibration can add significantly to the campaign cost. If the campaign allows for some flexibility in the tested sea state conditions, then it is recommended to perform a sea state characterization rather than a calibration. A characterization determines the sea state parameters (e.g. significant wave height, peak period, and spectral shape) actually achieved, rather than seeking to attempt an exact pre-determined sea state through wave tank calibration.

NOTE If testing is undertaken as part of a contest where several devices (potentially tested across multiple facilities) are in competition, then comparison between results is greatly eased by undertaking sea state calibration at each contributing facility, rather than simple characterization.

Setting up device mooring lines during Stages 1 and 2 can be challenging, and procedures might differ between facilities. It is recommended to make use of simple mooring setups that can be well characterized in terms of, for example, mooring stiffness. Unrealistically stiff or poorly connected mooring lines can introduce large load spikes that increase uncertainty.

Inadequate use of sensing equipment is a common cause of errors and uncertainty. For example, using an inclinometer (meant for static angles) for dynamic tests will give erroneous results due to incorrectly resolving the gravitational acceleration in a dynamic sense. Where possible, it is recommended to use redundant measurement systems, for example inertial based sensors (in the WEC) in combination with global optical motion tracking.

Insufficient record keeping is a very common cause of uncertainty. For example, making a change to a damping setting which is not noted in the experimental log would lead to erroneous subsequent interpretation of the experimental data. A detailed log shall be kept for all experimental activity. This log should include a separate entry (e.g. separate column in a table) for each parameter that is expected to be changed during the experimental campaign. For each test, each parameter should be logged, even if not changed between the previous and subsequent tests.

12.3 Accepted levels of uncertainty

As noted in 12.1, WEC model testing particularly at Stages 1 and 2 can be associated with higher levels of accepted uncertainty than what is common in more mature technology fields. To provide some guidance:

- By its very nature, Stage 1 testing is highly exploratory. An uncertainty of order 20 % for the device power capture and device loads is considered acceptable. The subsequent Stage 2 testing remains in a laboratory setting, where failure (e.g. mooring line breakage) is both unlikely and of relatively low consequence.
- During Stage 2 testing, it should be borne in mind that the testing results will directly inform the Stage 3 sea trial design. The accepted level of uncertainty should be differentiated between power performance and loads as follows:
  - For extreme load measurements, an uncertainty of under 10 % should be targeted. If 10 % uncertainty in the load values cannot be achieved, the subsequent Stage 3 design should apply higher factors of safety than would otherwise be recommended (see IEC TS 62600-2).
  - For power performance estimates, an uncertainty of up to 15 % is acceptable.
- For Stage 3, there will be a significant amount of uncertainty in both the conditions (uncontrolled environment) and in the technology (which is likely being tested for the first time). System commissioning and bench testing of the PTO (outlined in 5.5.4) shall support characterisation of the response and estimation of the uncertainties.

NOTE 1 During early stage testing, the PTO efficiency is likely poor. For Stages 1 and 2, the experimental apparatus is unlikely to overcome the net losses in the system, and little or no net (electrical) power is produced. During Stage 3, some net power might be produced, but overall PTO efficiency is likely to remain low. Efforts are hence focused on increasing certainty in capturing the force and motion response of the WEC. These force and motion responses can then be applied during subsequent bench testing of larger scale PTO units.

NOTE 2 An uncertainty example calculation associated with the laboratory testing of WECs is provided in [6].

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~~ commercial 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 document. This ordered approach also reduces the uncertainty of the ~~full-scale~~ commercial-scalepredictions 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.

Stage 2 (TRL4): During the medium-size device programme (Stage 2), a more sophisticated model, measuring specification and design regime, shall be adopted. All previous device metrics shall again be applied together with a full ~~third party~~ engineering techno-economic review of the device. The combination of the advanced test procedures and operational estimates result in reduced uncertainty of the full economic evaluation of the device. The advanced test requirements are specified in 4.4 and these are used as the basis to specify the Stage Gate criteria in 4.4.2.

Stage 3 (TRL5 and TRL6): The large-size model is a fully operational unit deployed at sea and testing in naturally occurring wave conditions.

A.4 Uncertainty factors

The underlying principle of the increasing scale (or staged) development programme is intended to naturally decrease the degree of uncertainty. The three primary sources of evaluation error are:

- Measurement inaccuracy during the testing.
- Limited test programmes.
- Scale factors during the prediction process.

Measurements: it is never possible to fully remove physical parameter measurement inaccuracy, or discrepancy, during a practical test campaign. However, they can be controlled and reduced by following the recommendations of this document. As the staged programme advances, improved sensors and data acquisition methods are recommended together with increased calibration verification. An improved model is also recommended by the document. An important aspect for controlling the monitored parameter uncertainty is to include statistically viable repeat testing.

Test programme: the test specification is advanced as the trials move through the stages. This includes both the environmental conditions the model is exposed to and the number of trials to conduct. Improper test planning and execution can introduce bias errors into the test results.

Scale factors: although Froude similitude laws should enable accurate values for most physical properties to be obtained, two concerns exist even at the smaller scale models. Firstly, not all parameters do follow the Froude similarity rules and, secondly, the adjustment factors required to estimate full-scale values can be large. For example, the device power scales with the length scale to the power of 3,5, such that the results measured in a 1:50 model multiply by a factor of 883883. Such multipliers do not instil confidence in the prediction to full size, and even if they are accepted in percentage accuracy, the absolute variability is still significant. The progressive increase in model scale is designed to reduce the scale factor distrust.

Each of the above factors shall be included in the Stage Gate appraisal process as specified in 4.3.2, 4.4.2 and 4.5.2.

Annex C and Annex D provide background information on performing recommended uncertainty estimates.

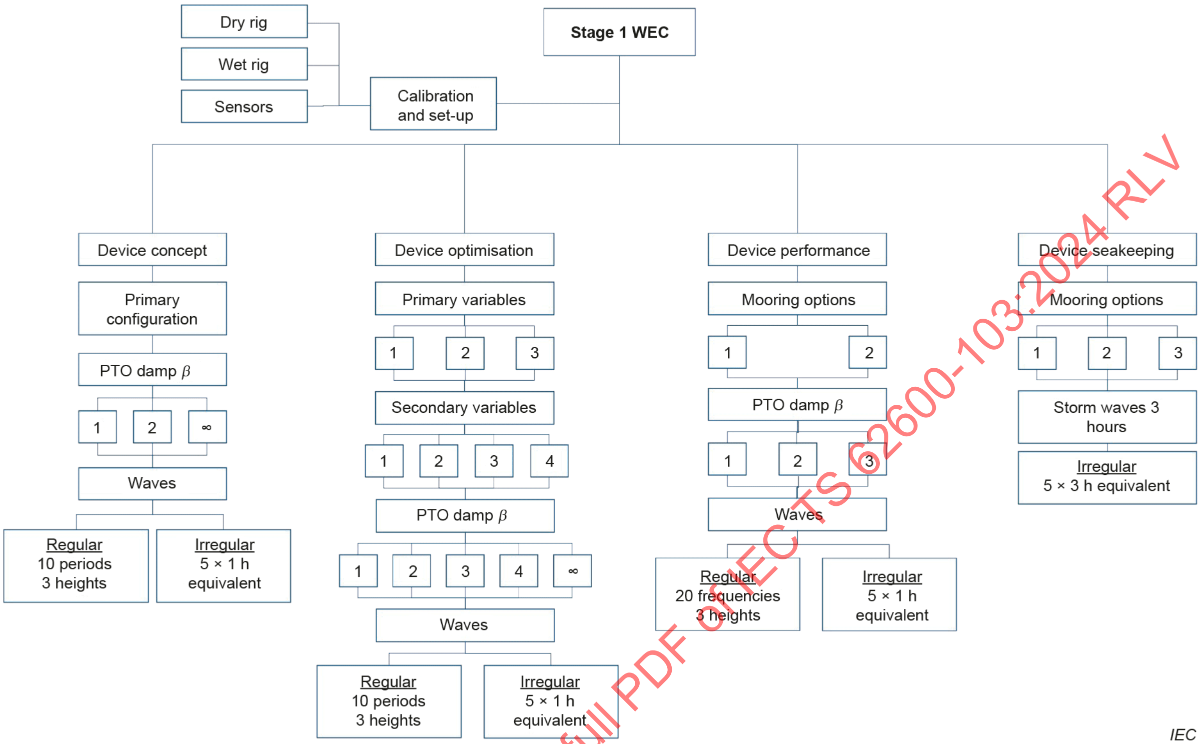
A.5 ~~Third party~~ Concept review

It is not uncommon that device concepts, tested as idealised small models, particularly in Stage 1, can initially prove successful as energy converters but ~~may~~ might have inherent technical problems that make full size, prototype engineering impractical. The initial design might also create difficulties when advancing to a stage requiring certification and insurance before sea trials can be undertaken. It is recommended that detailed engineering reviews of the device are undertaken as part of the Stage Gate process, even at the initial concept scale, to reduce the possibility of this failure mode occurring after considerable effort has been invested in the device development.

These engineering reviews can be undertaken internally if the development team has the appropriate skill set but since the range of evaluation criteria is quite broad, including naval architects, power take-off specialists, mooring designers, power electronics and communication experts, the use of established engineering consultants is recommended. Besides possessing a wider range of experience, the independence of a consultant can prove advantages when attempting to secure the next phase of funding.

Annex B
(informative)

Example test plan



NOTE The test plan is important to ensure all the device variables and environmental conditions are included at each Stage of development and to facilitate the initial time estimates to conduct the test programme.

Figure B.1 – Example test plan

Annex C
(informative)

Physical modelling guidance

C.1 Similitude

C.1.1 General

This annex provides general guidance on similitude in physical modelling.

C.1.2 Geometric similitude

Geometric similitude is the reproduction of the WEC geometry, mass distribution, and centres of buoyancy gravity and metacentre at distinct scales. Geometric similitude for the mooring system is often not met in model scale testing due to the size of the testing facilities. However, since the main influence of the mooring system on the WEC is related to the pre-tension and the stiffness curve in relation to an external environment, geometric similitude of the mooring system is not viewed as critical in most scaled testing.

C.1.3 Structural similitude

Structural similitude is the reproduction of the structures response to external load, for example hydro-elasticity. The non-dimensional Cauchy number relates the influence of the inertial forces to the elastic forces. Here, the stiffness and stresses induced in an elastic structure through the interactions with the environment are desired to be reproduced. Clearly for "rigid" structures (WECs to be built with materials with large Young's moduli), the elastic nature of the WECs response ~~may~~ might not be dominant. However, for structures that are designed to be built with deformable materials, which are central to the WECs response in the environment, it is clear that structural similitude will be dominant.

Structural similitude for the WEC is viewed as critical in Stage 3 testing. Additionally, there are particular designs and sub-system tests in Stage 2 that will also require structural similitude. However, in most Stage 1 and Stage 2 tests, the model is generally considered a rigid structure, hence resulting in structural non-similitude.

A specific goal of a Stage 2 test may be to determine the slamming pressures that are to be expected in ~~survival~~ extreme conditions. This goal would require that a portion of the structure is modelled to represent the elastic properties of the prototype. If this does not occur, the measured pressures cannot be directly scaled-up. Further, it could be that a "rigid" prototype exhibits large elasticity along a particular dimension, for instance very long WECs. In this case, specific model building techniques can be adopted to mimic the longitudinal bending by breaking the structure into segments and introducing the elasticity at the segment connection points.

Structural similitude for the mooring system is viewed as critical in Stage 2 and Stage 3 testing. In these Stages, the pre-tension, stiffness curve as well as the loads experienced by the WEC at the connection points, shall be reproduced in order to increase the accuracy of the scaled-up results. It is possible that the only way to achieve full structural similitude for the mooring system, in ~~survival~~ extreme tests for instance, is to achieve geometric and hydrodynamic similitude.

C.1.4 Hydrodynamic similitude

Selection of an appropriate hydrodynamic scaling law is based on an evaluation of whether gravity or viscous forces are dominant. Several scaling laws are described in the following sections. Table C.1 provides scale-up values based on Froude or Reynolds scaling laws and geometric similitude where λ is the geometric scale. Table C.1 assumes that density and gravity do not change between the prototype scale and the model scale.

Froude similarity: the non-dimensional Froude number relates the influence of inertial forces to gravitational forces. Froude scaling is used in model scale WEC testing because the majority of forces experienced by a WEC device are inertial and gravitational. Typical Froude scale factors are of order 1:25 – 1:100 (Stage 1), 1:10 – 1:25 (Stage 2) and 1:2 – 1:5 (Stage 3), where these ranges may also overlap between stages.

Reynolds similarity: the non-dimensional Reynolds number relates the influence of the inertial forces to the viscous forces. Fundamentally, this means that a model cannot meet both Froude scaling and Reynolds scaling criteria in the same model. The Reynolds number for a Froude-scaled model is smaller by a factor of $\lambda^{1,5}$. Hence, while the prototype flow regime may be turbulent, the model may be laminar. The drag coefficients in laminar flow are normally higher than those found in turbulent flow. Hence the scale-up is generally expected to underestimate the true performance of the WEC. The level of underestimation is directly related to the dominance of viscous losses in the design. Currently there is no guidance on the relation between underestimation, the WEC scale, and the WEC design elements. The larger the scale of the WEC device, the less dominant the scaling mismatch will become.

Significant additional guidance and background on scaling laws can be found in [16].

Table C.1 – Scale laws

Characteristic	Parameter	Froude scaling	Reynolds scaling
Geometric	Length	λ	λ
	Area	λ^{2}	λ^{2}
	Volume	λ^{3}	λ^{3}
Environment	Wave height and length	λ	λ
	Wave period	$\lambda^{0,5}$	λ^{2}
	Wave frequency	$\lambda^{-0,5}$	λ^{-2}
	Power density (per unit length)	$\lambda^{2,5}$	λ^{4}
Kinematic	Translational displacement	λ	λ
	Angular displacement (rad)	1	1
	Translational velocity	$\lambda^{0,5}$	λ^{1}
	Angular velocity	$\lambda^{-0,5}$	λ^{-2}
	Translational acceleration	1	λ^{-3}
	Angular acceleration	λ^{-1}	λ^{-4}
	Volume flow	$\lambda 2^{,5}$	λ
Dynamic	Mass	λ^{3}	λ^{3}
	Force	$\lambda 3$	1
	Torque	λ^{4}	λ
	Pressure	λ	λ^{-2}
	Power	$\lambda^{3,5}$	λ^{-1}
	Translational stiffness	λ^{2}	λ^{-1}
	Angular stiffness	λ^{4}	
	Translational damping	$\lambda^{2,5}$	λ
	Angular damping	$\lambda^{4,5}$	λ^{3}

C.2 Model instrumentation and data acquisition

C.2.1 General

The purpose of this clause is to provide guidance concerning the following key sensing aspects:

- Sensor appropriateness.
- Sensor alignment and positioning.
- Sensor / model interactions.
- Sensor calibration best practice.
- Drift and environmental sensitivity of sensors.

Each of the above aspects will be discussed in the context of the relevant physical quantity to be recorded. The description is limited to the most commonly used techniques, and an experienced tank operator should be consulted for any specialised instrumentation.

C.2.2 Water surface elevation

In most wave tank laboratories, the surface elevation measurement relies on conductive or capacitive wave probes. Conductive types ~~need to~~ should be calibrated daily during model testing. If capacitive types are used, the calibration in commonly checked at regular intervals, at least twice weekly. If used within their recommended minimum immersion depth (to avoid probe end effects), both types of probes are expected to exhibit linear behaviour. The probe linearity can be confirmed through calibration. Calibration normally includes a minimum of three points, with five points being recommended. Surface elevation probes are small devices, and do not generally interact with the physical model and the incident wave field. The frequently used resistive type wave probes drift with changing water temperature and water chemical composition (conductivity). Additional calibrations are recommended if the water conductivity is likely to change significantly during testing. A recommended good practice is to recalibrate select sensors at the end of the test program to quantify drift.

C.2.3 PTO

Very accurate measurements of both the applied PTO dynamics (force, pressure or similar) and the PTO kinematics (velocity, flow rate or similar) are required. Special attention shall generally be paid to accurately record the phasing between these two signals.

Optical encoders are commonly used to measure the kinematic component of the PTO. Where possible, it is recommended to use absolute rather than incremental encoders. It is not uncommon for encoders to miss pulses, e.g. due to a dirty disc, resulting in loss of accuracy for incremental encoders.

If an incremental encoder is used, then it is recommended to also measure the index pulse so that an absolute position can be referenced.

C.2.4 Device and mooring loads

Where mooring loads are of concern, these are often measured using an inline (single DoF) load cell. The load cell calibration can be confirmed as part of the dry testing.

Where the WEC is attached directly to the sea bottom, a six DoF load cell is recommended to record the foundation loads. This type of load cell requires calibration in all DoFs, and cross-coupling between the DOFs often arises.

If fluid impact pressures are of concern, these are best recorded using a pressure sensor or small-footprint load cell. This type of sensor can be integrated into the hull of the device. It is important to note that each sensor is characterised by a distinct frequency response. With pressure rise times in the order of several milliseconds at laboratory scale, the sensor response may affect the measurements.

C.3 Recommendations on calibrations

Most sensors and instrumentation applied in model testing require calibration, most notably wave probes. Commonly applied calibration routines for typical WEC testing related sensors are described in Table C.2.

Where appropriate (for example load cells) tare readings should be taken daily. To avoid thermal drift, the sensor should be powered on for at least ten minutes before taking the tare reading.

Table C.2 – Sensor calibrations

Type	Method	Notes
Capacitive wave probe	Use 3 to 5 point calibration, most commonly with linear fit.	Insulation characteristics (dielectric constant, thickness, etc.) will affect response per unit length.
		A sufficient length should be immersed at all times.
Resistive wave probe	Use 3 to 5 point calibration, ideally daily, most commonly with linear fit.	Based on known immersion to voltage relationship.
		Nonlinear towards the probe end.
		A sufficient length should be immersed at all times.
Distance sensor (laser or potentiometer)	Recommended to confirm relationship using a mechanical reference height gauge.	Known distance to voltage relationship available from data sheet.
Pressure cell (piezoelectric)	Follow manufacturer-supplied method.	
Load cell (strain gauge)	Calibrate against set of reference weights using supplied data sheet sensitivity value (mV/V).	If a multi-axis load cell is used, each axis requires calibration.
Multi-degree of freedom motion tracking system	Shall be calibrated in 3-dimensional space.	Fairly advanced calibration which should be left to experienced system or tank operator.
Inertial Measurement Unit (IMU)	Move in known trajectories with known rates in 3-dimensional space.	
Accelerometer	Move in known trajectories with known rates in DoF.	
Tilt sensor	Measure response for series of known angular offsets.	
Pressure gauge	Both static and dynamic calibrations using pumps.	

Annex D
(informative)

~~Uncertainty~~ Scale effects

~~The scaled development programme described fully in [14] and in part in this document is structured to de-risk the extensive process of engineering a product from concept to commercial deployment. However, there are still three basic sources of uncertainty encountered at each of the Stages of the testing that shall be accommodated during the evaluation process:~~

- ~~The variability of measured physical properties during testing; this uncertainty is encountered in all fields of science and how to quantify the error is well described in several publications, such as, [7], [15], [16], and [17] through [21].~~
- ~~The inability to scale all physical properties within one of the standard similitude approaches; this testing dilemma is covered in Annex C.~~
- ~~The error introduced when projecting up the device parameters through the scales; this source of uncertainty is the basis of the increasing model size / decreasing scale development structure described.~~

~~Measurement error: a certain amount of discrepancy in measured values should always be expected and accepted in a test programme. There are experimentation techniques that can be followed to contain this uncertainty, as outlined throughout the relevant clauses. The two primary methods to reduce, or quantify, the variability are:~~

~~a) Careful selection when specifying the physical property monitoring sensors such that they fall within the limits of accuracy required for the different sized models. Static or dynamic calibration of the sensors, as required, can further contain the uncertainty by improving the absolute measuring accuracy and ensuring there is no bias in the data.~~

~~b) Run repeat tests as often as practical such that the measuring error can be qualified and statistically established. These sources of error are described in detail in several ITTC documents and in particular Recommended Guideline 7.5-02-07-03, Wave Energy Converter Model Test Experiments.~~

As stated in Annex C, it is often not possible to scale all physical properties during a specific testing campaign. Since this source of uncertainty ~~increases for the smaller scales~~ decreases as the scale factor decreases, the development schedule is linked to progressively decreasing the model scale as the test programme advances. This approach not only gradually reduces the effect non-scaled parameters have on the results but also enables the previous sized model data to be checked and errors quantified. Careful configuration of the test plan will enable the previous scale results to be corrected and the technical conclusions verified.

Scale ~~up of results: the two error sources outlined above~~ effects contribute to ~~overall discrepancy when the various measured parameters~~ the overall discrepancy when the various measured parameters are scaled by the appropriate indices as shown in Table C.1. Since this multiplier increases by the parameter power, large products of the results are inevitable. For example~~, as outlined in the relevant clauses~~, the absorbed device power is the product of the scale raised to 3,5 ~~($\lambda^{3,5}$)~~. Table D.1 describes the typical multipliers for each of the 5 Stages of development.

Table D.1 – Scale example for absorbed power

Stage	Typical scale (example)	Froude multiplier for absorbed power (example)	Power per MW (example)
1	1:50	883 883	1 W
2	1:15	13 071	77 W
3	1:4	128	7,8 kW
4	1:1,5	4	250 kW
5	1:1	1	1 MW

As can be seen from these values the influence of the scale is quite significant on the power conversion of the various models such that any discrepancies in the testing can result in large errors when the results are scaled up. Theoretically, if tests are conducted correctly and carefully the percentage error should remain the same throughout the scales and only the absolute value seems different. However, in practice, the uncertainty of the data leads to extra care being required when evaluating early Stage results. The ITTC provides guidelines for assessing uncertainty for scale up and extrapolations, [14] and [15].

~~Example: an uncertainty example calculation associated with the laboratory testing of WECs is provided in [7].~~

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IEC TS 62600-103

Edition 2.0 2024-07

TECHNICAL SPECIFICATION

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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

IEC TS 62600-103:2024-07(en)

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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

FOREWORD

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

This second edition cancels and replaces the first edition published in 2018. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) Revised several numeric values (e.g. test durations) to align with best testing practice;
b) Introduced guidance and requirements relating to PTO testing and closed-loop control;

c) Introduced uncertainty clause in normative part of the document;

d) Strengthened the document sections relating to Stage 3, the first sea trials;

e) Updated the data synchronisation requirements to align with best testing practices.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
114/510/DTS	114/523/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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 webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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 document 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 Clause 2 and Clause 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 (Clause 9 to Clause 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), data acquisition and real-time control (Clause 8), and testing uncertainty Clause 12 are also included.

The structured development schedule makes use of the ability to accurately scale wave energy converters 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 wave energy converter'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 wave energy converters since it takes a professional approach to the process.

An essential element for any published Technical Specification or International Standard is to allow an opportunity to provide feedback on its contents to the appropriate TC 114 Working Group. TC 114 utilizes a standard methodology to allow this.

To submit feedback such as proposed changes, corrections and/or improvements to this document, please send an email to the TC 114 Chair using the Contact TC 114 Officers feature on the IEC TC 114 Dashboard, accessible at www.iec.ch/tc114. On the right side of the Dashboard under Further information select the link to contact the TC 114 Officers. On the subsequent page find and select the Send Email link for the Chair to access the email tool.

Complete all the required elements within the email pop-up. For the Subject field please include the document title and edition you are providing feedback for (ex: feedback for TS 62600-1 ED2). In the Message field, include text which summarizes your feedback and note if further information can be made available (note attachments are not allowed). The Chair may request added information as needed before forwarding the submission to the remaining TC 114 Officers for review and then to the appropriate Working Group for their consideration.

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 wave energy converters (WECs). It includes wave tank test programmes, where wave conditions are controlled so they can be scheduled, and first sea trials, where sea states occur naturally and the programmes are adjusted and flexible to accommodate the conditions. Commercial-scale prototype tests are not covered in this document.

This document prescribes 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. Provided 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 defendable results of defined uncertainty.

This document serves 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 62600-2, *Marine energy – Wave, tidal and other water current converters – Part 2: Marine energy systems – 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, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions 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

3.1.1
dynamic
forces responsible for the object's motion

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

3.1.2
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.

3.1.3
operational sea states
wave conditions where the wave energy converter is in power production mode

3.1.4
peak distribution
distribution of peak magnitude values

3.1.5
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.

3.1.6
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.

3.1.7
stage 3 <of wave energy converter testing>
first testing at sea

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

3.1.8
storm conditions <of a marine energy converter>
sea state with return period as defined in IEC TS 62600-2

3.2 Symbols and abbreviated terms

For the purposes of this document, the following symbols and abbreviated terms apply.

g	Acceleration due to gravity	[m/s^2]
H	Wave height	[m]
H_{m0}	Significant wave height	[m]
J	Wave energy flux	[W/m]
P	Wave power	[W]
T	Wave period	[s]
T_e	Wave energy period	[s]
T_p	Wave peak period	[s]
T_z	Zero up-crossing period	[s]
λ	Length scale factor	[-]
θ	Wave direction	[rad]
ρ	Density	[kg/m^3]

AD	Analogue to digital
CoG	Centre of gravity
DAQ	Data acquisition
DFT	Discrete Fourier transform
DoF	Degree of freedom
FFT	Fast Fourier transform
FMECA	Failures mode, effects, and criticality analysis
IMU	Inertial measurement unit
OWC	Oscillating water column
PCC	Power conversion chain NOTE The power conversion chain is made up of a drivetrain, generator, storage, and power electronics.
PTO	Power take-off
RAO	Response amplitude operator
SCADA	Supervisory control and data acquisition system
SWL	Still water level
TRL	Technology readiness level
ULS	Ultimate limit state in the context of structural engineering
WEC	Wave energy converter

4 Staged development approach

4.1 General

Clause 4 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 commercial scale (or near commercial 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 Clause 5 to Clause 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. The criteria are defined as a general framework and allow for a high degree of flexibility to suit the 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.

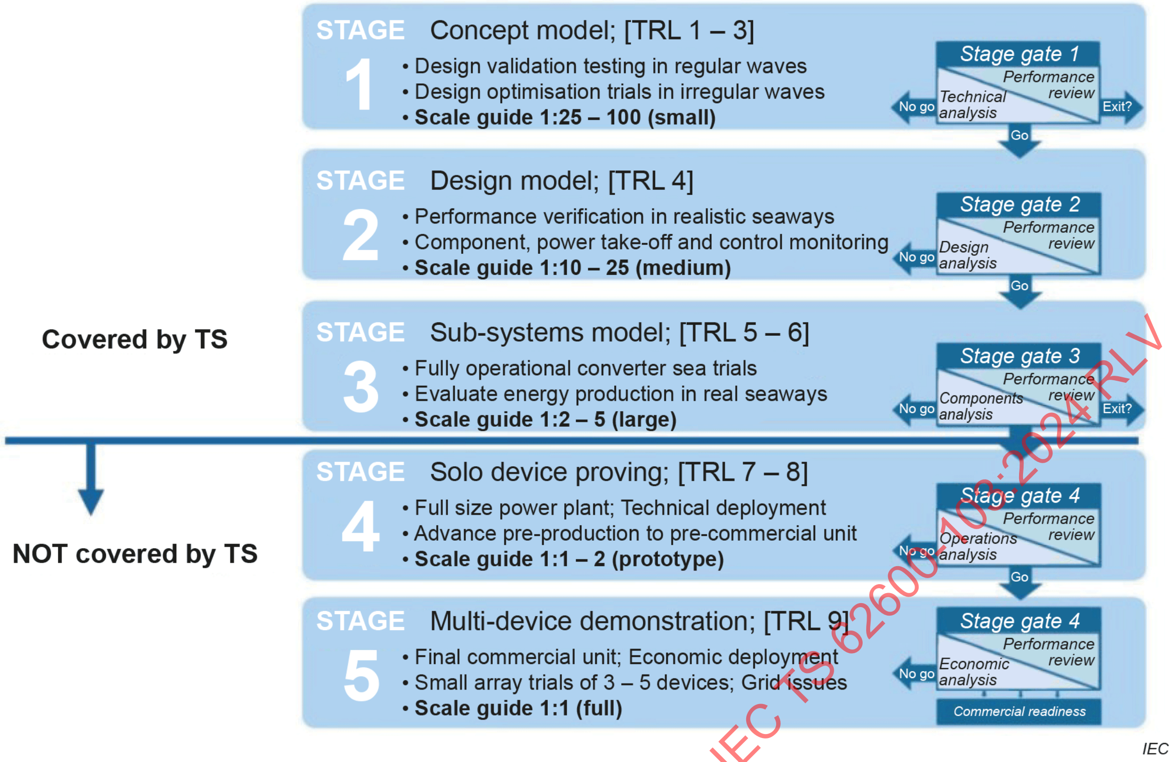

Figure 1 – Staged development approach

4.2 Stage gates

4.2.1 General

At the conclusion of each stage of device model testing, an evaluation procedure should be initiated 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 Clause 9, Clause 10 and Clause 11. As the test scale enlarges, the complexity of the model and trials increase to produce more accurate results with less uncertainty in the data 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 specifications for each Stage Gate criterion that experimental testing can contribute to are outlined in Clause 9, Clause 10 and Clause 11 and summarised below.

Each stage can comprise more than one model testing campaign, using progressively optimised models, to maintain relevance as the device design progresses, and to comprehensively meet the Stage requirements and Stage Gate criteria.

NOTE Physical model testing is often run in conjunction with a mathematical model development, with model validation criteria similar to those listed in Clause 4.

4.3 Stage 1

4.3.1 Scope

Stage 1 is intended to demonstrate that the design has potential and can 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 several device configurations without a detailed design for the commercial 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 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 can 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 forcing 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 wave spectra distributions. This includes white or pink spectra for system identification purposes.

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

The methodology of testing recommended here follows established best practice for Stage 1 testing. The results of this stage are lessons used to converge on a commercial-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:

- a set of power response transfer function (RAO, for similar wave heights);
- power capture prospects estimated from selected sea states, with details provided in Clause 9.

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.

NOTE For a simple model with linear PTO damping, power absorption generally scales with the velocity squared, or the wave height squared. It can hence be beneficial to express the power response as a quadratic transfer function of form Power/Height^2, rather than an RAO that is of the form Power/Height.

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 commercial-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 extreme 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 model, exhibiting an accurate representation of the proposed commercial-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 commercial-scale values with appropriate factors of safety. The data shall also (i) be suitable to confirm any mathematical or numerical models of the device where available; and (ii) be capable of extrapolation beyond one deployment location.

For validation of the Stage 1 results, both the wave and the device parameters should 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 settings) that supported the main Stage 1 conclusions. The medium-scale model can 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:

- a power response transfer function (RAO, for similar wave heights);
- power capture estimate based on a selected number of standard sea states (power matrix), with details given in Clause 9.

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 demonstrate in smaller scale the operating principles in "real world" uncontrolled wave conditions before building a commercial scale prototype many times more expensive. Stage 3 sea trials are conducted to prove the whole WEC system 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 i.e. survivability.

There are several purposes for conducting testing at this stage, ranging from advanced technical and engineering issues, through to 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;
- corrosion check: Using materials 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 is likely to 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 grid emulator can substitute for connection to a grid.

The selected scale should strongly consider the overlap of wave heights and periods between the commercial site and the test site when appropriately scaled using Froude scaling. For sea-floor mounted devices, the scale of the model should preferably be chosen as the ratio between the water depth at the anticipated commercial site and the water depth at the test site. This recommendation is also advised, though less critical, for other WECs such that other systems (moorings, umbilical, etc) are representative.

The scale should be used to scale any other parameters that affect the device and its subsystems. One issue can be the scaling of the water level variations and the local currents.

A comprehensive sea trial programme shall be developed for Stage 3 that provides sufficient confidence to move towards a commercial-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 a well-defined set of trials will provide data as significant as commercial scale but with a significantly reduced budget and technical risk.

NOTE Selecting an appropriate Stage 3 site is a challenging process, and the perfect site that suits all scaling and testing criteria might not exist. Some locations offer ideal water depth but not sufficient wave action, some locations meet the wave height criteria but do not scale well in terms of wave periods, and some locations provide the ideal wave climate, but only for very limited times during the year. To ensure that all testing objectives can be met, Stage 3 testing can be undertaken at more than a single location, where each location can meet part of the overall objectives.

4.5.2 Stage Gate 3

The Stage Gate in this case includes:

- the evaluation and verification of the PTO efficiency and control;
- the evaluation and verification of risk and safety management;
- the evaluation and 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;
- the evaluation of structural loads.

Partial verifications are often undertaken before sea trials commence. For example, evaluating the PTO efficiency and control can be undertaken 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);
- PCC 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 PCC 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 to limit magnification of viscous forces that are not expected to be representative of full-scale effects.

NOTE 1 Inaccuracies might be introduced through Reynolds, structural, and PCC 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 decreases.

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 can 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 frictional effects, like stiction, or non-physical hysteretic effects. Further, these representational PTOs might 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 anticipated commercial-scale 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 commercial-scale approach through the desired dynamic-kinematic characteristics.

NOTE 1 It is more common for 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.

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.

a) 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 commercial 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.

b) 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 commercial scale and the experimental design at model scale;
- definition of the anticipated commercial-scale PTO and its characteristics;
- supporting calculations to provide approximate device physical properties and behaviour;
- technical drawing of the preliminary mooring design in anticipated commercial 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, significant wave height, spectral representation and directionality, spreading coefficient (see IEC TS 62600-101 for details);
- indicate the scale to be used on the above site conditions to fit the model tests at each scale (see Annex D Table D.1).

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.

c) 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, significant wave height, and if available spectral representation and directionality, spreading coefficient (see IEC TS 62600-101 for details). Additionally, an estimate of the anticipated deployment length required to sufficiently meet the testing goals;
- appropriate checks for scaling of operating sea states and extreme seas;
- appropriate checks for scaling of water depth, water level and currents;
- 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 Clause 9, Clause 10 and Clause 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 [4].

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 site selection:

- Appropriate spatial and temporal wave condition in both amplitude and period.
- Appropriate water depth for mooring fidelity.
- Sea bed conditions to suit mooring requirements.
- Local (rapid) changes in sea bed conditions that are likely to affect testing.
- Convenient launch and deployment facilities, and particularly vessel availability.
- Local service and maintenance amenities.
- Land-based data station.
- Appropriate atmospheric and oceanographic conditions, such as the absence of rip currents, large tidal variations, tidal races, 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, see 4.5.1 for details. 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 can be run by a State or private entity. 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 extreme conditions.

Stage 3 extreme testing is sought to achieve conditions that get close to true extreme conditions. Many interpretations of such testing conditions are possible and are to be noted in the reporting. Example interpretations 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 might also occur at such sites.

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
- Water level variations (or tidal range).

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

5.4 Physical model considerations: Absorbing body and mooring system

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.
- Mooring simulation to match desired device dynamics.

Several physical models can be used to complete the end goal of the overall 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 commercial-scale device.
- The mooring system shall 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. This Stage 3 device might be a significant model on the order of many tonnes and 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 it is not necessary for the scaled device to be grid connected and an alternative method of power dissipation, for example 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 load paths within the device structure.
- Accurate and complete assembly procedures.
- Instrumentation required to record required data streams including sensor redundancy.
- Supervisory control and data acquisition system (SCADA).
- Efficiencies in the PCC.
- Accurate mooring designs and assembly procedures.
- Safety of workers during commissioning, 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. A PTO simulation can initially be installed to validate and verify the system hydrodynamics.

The detailed Stage 3 WEC hull design and fabrication is commonly undertaken by a specialist marine contractor. Hull design and fabrication are not within the scope of this document, and reference should be made to the appropriate guidelines and standards for marine fabrication.

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

5.5 Physical model considerations: PTO and closed-loop control

NOTE Subclause 5.5 is written with closed-loop feedback control in mind. For devices that do not feature closed-loop feedback control, some of the requirements here only apply in part.

5.5.1 General

It is important to recognize that closed-loop absorption control for WECs introduces effects that are quite different from those in open-loop marine systems such as vessels. At the onset of the design process, a basic understanding of closed-loop control theory should be developed. This includes aspects of system design such as considering the modes of drivetrain resonance and how these might be excited via closed-loop feedback control.

The PTO strongly affects the device performance. In general, the PTO works by applying a force on the WEC that depends upon the WEC motion. A simple damper, for example, applies a force that is proportional to velocity. The force can be applied by a mechanical damper or by a sophisticated device that measures the velocity and generates a force by means of an actuator, which is commanded by a control system. In both cases, the dynamic behaviour of the coupled PTO-WEC system differs from the behaviour of the WEC when disconnected from the PTO. As a result, the developer should characterize the behaviour of the PTO to characterize its effects on the device once installed and deployed for tank testing or sea trials.

The implementation of a control system can dramatically improve power absorption performance or can, in the extreme case, destroy the device through instability. Therefore, for any device that uses feedback control, close attention shall be paid to the closed-loop dynamic properties of the controlled PTO.

NOTE Problems due to stability commonly arise when feedback controllers are implemented. These issues are often due to the PTO not being properly designed to execute the desired control system, for example not being able to apply the desired level of damping.

Tuning of mechanical power versus electrical power can lead to very different PTO optimization outcomes. Each Stage 1-3 testing campaign should clearly identify the PTO optimization objective, for example to maximize mechanical power or to maximize electrical power at a defined conversion step.

A PTO and control system will ultimately only function if all system components work in unison. This commonly includes the PTO hardware (actuators, gearboxes, hydraulic circuits etc.), the instrumentation feeding into any active control system, and the real-time control system hardware and software. The PTO design process should identify all critical PTO component, and how these can be reliably integrated into an overall system. The PTO hardware (e.g. actuators) is likely very different between Stages 1 and 2, and Stage 3. The PTO characterization shall be repeated each time the PTO hardware changes substantially.

5.5.2 PTO and control design considerations for Stages 1 and 2

During a Stage 1 program, the PTO can be represented using a simplified, yet well-characterized mechanism.

During a Stage 2 program, the PTO shall be represented using a mechanism capable of exhibiting the proposed (or intended) commercial-scale kinematic and dynamic PTO characteristics and control strategy. If the commercial-scale or Stage 3 device relies on a closed loop feedback controller, then a closed loop feedback controller is also recommended during the Stage 2 model testing.

NOTE 1 The detailed design of the first sea-going (Stage 3) device often takes place following the Stage 2 model testing. As a result, either the Stage 3 or the commercial-scale PTO hardware, or both, might not be fully defined during the Stage 2 testing. Nevertheless, having a proposed or intended PTO concept in mind prior to Stage 2 model testing is key for the success of the overall staged testing approach, such that the intended kinematic and dynamic PTO characteristics can be tested during Stage 2.

NOTE 2 Matching the kinematic and dynamic behaviour is particularly important if the PTO at commercial scale is capable of providing significant amounts of reactive power. In this case, the motion of the WEC will be amplified by the interaction with the controlled PTO, and the wave-body response can be significantly different from the case where no PTO is included.

5.5.3 PTO and control design considerations for Stage 3

During a Stage 3 program, the PTO shall be represented using a mechanism capable of exhibiting the proposed commercial-scale kinematic and dynamic PTO characteristics and control strategy. If the commercial-scale device relies on a closed loop feedback controller, then a closed loop feedback controller shall also be tested during the Stage 3 sea trials.

The device power can be measured at various conversion steps, for example mechanical input power, and reported at those points. For each reported power performance value, it shall be documented exactly where in the PCC this power is recorded.

NOTE While peak power ratings for Stage 3 can be several kWs, continuous power flow in many sea states is likely of the order of several hundred Watts. As a result, efficient electrical power conversion (and potential transmission to shore) can be very challenging.

Stage 3 is the first stage that involves open water sea trials. The Supervisory Control and Data Acquisition System (SCADA) shall be designed such that it can handle autonomous operation of the WEC. The SCADA system can rely on manual intervention for certain tasks (e.g. switching between various control strategies) but shall be designed such that safety and seakeeping critical features do not rely on real-time operator input. The SCADA system 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 system.

5.5.4 PTO bench testing

Bench testing time is significantly less expensive than wave tank testing time (Stages 1 and 2) or sea trials (Stage 3). The key purpose of a PTO bench test is to identify the main issues and faults with the PTO design, such that the PTO integrated with the device is pre-tested and reliable [5]. This can greatly reduce the likelihood of failure of a wave tank or at sea testing.

There are two main types or purposes of PTO and control bench tests:

a) Characterize, verify, and validate an open-loop model of the PTO: This is useful for both the design of the controller and evaluation of performance and efficiency. With regards to control design, the model derived from experimental testing is useful also to establish the bounds on the controller performance (type of controller and range of stability margins);
b) Test control system: Verify closed-loop PTO behaviour before tank testing or sea trials.

It is recommended to undertake the first type, (a) above, for Stages 1 and 2. The second type, (b) above, should be undertaken for Stage 2.

Both (a) and (b) above shall be undertaken for Stage 3. The Stage 3 PTO is the first larger PTO assembly for most WEC developers, likely with actuators capable of delivering and accepting several kWs of power. Bench testing of the PTO drive train shall be undertaken prior to integrating the PTO within the Stage 3 WEC model. During this bench testing, the Stage 3 PTO drive train is likely to exhibit some unique behaviour (e.g. drive train resonances) that cannot be scaled to a commercial-scale device. Nevertheless, any such (resonant) behaviour should be documented to inform the commercial-scale device design.

NOTE It can be challenging to find a bench test laboratory for every type of Stage 3 PTO. For some shoreline OWC devices, sometimes the WEC system itself is the test bench for the PTO system.

Bench testing of PTO components can be undertaken using simplified device models, such as simple mass-spring-damper systems. Components of the real physical system can also be simulated using hardware-in-the-loop techniques. The key to bench testing is that the PTO hardware and control system are shown to be operating with good stability margins before being integrated into the WEC model for wave tank testing or sea trials.

During Stage 3 bench testing, the principal PTO control algorithms shall be tested as intended for the Stage 3 sea trials. This shall include executing those algorithms on the intended sea trial computing hardware (SCADA system). It is acceptable that not all physical sensors are present during the bench testing phase, and sensor signals can be simulated as required.

It is recommended that the PTO test stand is capable of compliant PTO excitation. In this context, compliant refers to the ability of the PTO test stand to react to the PTO forcing, rather than rigidly enforcing a motion profile that is not representative of the coupled interactions between the PTO and the wider WEC system.

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 commercial-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 either model or full-scale values, or both, 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 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 1 It is often helpful to also present subsets of the raw data time series.

NOTE 2 In calculating error bars, the uncertainty analysis in [6] can be helpful.

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. Clause 9 provides details concerning the number of regular waves to be considered. Error bars should be associated with both the abscissa and ordinate axes. The appropriate uncertainty analysis (see Clause 12) 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, 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 bivariate 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 can 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 can contain entries relating to a number of control settings.

For Stage 3 sea trails, it might 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 should be associated with both the abscissa and the ordinate axes.

NOTE In calculating error bars, the uncertainty analysis in [6] can be helpful.

6.2.5.2 Capture width and capture width ratio

The capture widths for the individual tests shall be calculated based on 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. The characteristic dimension used shall be clearly stated. Either the capture widths or capture width ratios, or both, shall be plotted against peak period of the spectrum. The measured model scale data should be presented. Predictions for commercial scale can be included. Typically the sea state over a test interval of 20 minutes will be given by the significant wave height estimate H_{m0} and wave energy period T_{e}.

NOTE These calculations can be presented at commercial scale or in terms of non-dimensional parameters, e.g. wave steepness, H_{m0}/T_{e}, and relative length l, characteristic device length λ_{e} normalised by wave length (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 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 and 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 of 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 ± Std. Dev. <Peak> ± Std. Dev.	Average ± Std. Dev. <Peak> ± Std. Dev. <Phase of Peak> ± Std. Dev. <Peak> to Average ± 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 of performance indicators in irregular long-crested waves

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 waves. 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 ± Std. Dev. <Peak> ± Std. Dev. Peak	Average ± Std. Dev. <Peak> ± Std. Dev. <Peak> to Average ± Std. Dev. *Spectral response*: indicate the moments of the spectrum *Peak distribution:* indicate probability density function parameter values, mean, median, and 98th 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) can 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 ± Std. Dev. <Peak> ± Std. Dev. Directional spectral response *Peak distribution:* identify 98th percentile	Average ± Std. Dev. <Peak> ± Std. Dev. Directional spectral response *Peak distribution:* identify 98th 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:

a) calibration of the incident waves undertaken in the absence of the structure;

b) 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;

c) 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 [7]).

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 minimum required measurements for each aspect or type of the incident environment. Additional wave probes are recommended if the incident and reflected waves from the device are to be separated.

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 3 measurements during tests: in front, behind, and flanking one 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 3 measurements during tests: in front, behind, and flanking one 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 50 m 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 can 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 should 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 the water surface elevation (wave elevation recorded at the surface), and calibration of the water surface elevation only might 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 [8]. 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, either time or frequency domain analyses, or both, 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 [9]. 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 [10]. 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. 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 [11]. 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 diagram 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, ± Std. Dev. Wave period T, ± Std. Dev. Wave direction θ, ± Std. Dev.		N/A
	Irregular long-crested waves	Significant wave height, H_{m0} 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 document refers to the methods established for open-sea characterisation in IEC TS 62600-101.

8 Data acquisition and real-time control system

8.1 Signal conditioning

Data acquisition is a rapidly evolving field, and this clause only serves as a brief overview. If in doubt, an experienced instrumentation engineer or the test facility should be consulted.

Modern DAQ systems often rely on distributed fieldbus protocols, where the analogue signal can readily be converted to a digital signal close to the signal source. Distributed fieldbus systems avoid issues with long analogue cable runs and associated noise and are hence recommended where possible. Where long analogue cable runs cannot be avoided, current loops (typically 4 mA to 20 mA) are recommended, or alternatively, sensors with analogue voltage outputs should be calibrated with the cable length included.

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:

a) The sensor lead should be kept as short as possible and the analogue to digital (AD) conversion should be undertaken in close spatial proximity to the sensor.
b) An instrumentation amplifier should be placed as close as possible to the sensor, providing a more robust electrical signal.
c) Where longer cables are necessary, appropriate measures shall be taken to minimise errors due to noise and damping of signals. This can rely on techniques such as twisted and shielded pairs of wires, or measuring methods employing long cable compensation (e.g. 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 have a sensitivity in their output to other factors such as temperature or vibration, might need to be corrected for these factors. Thus, these additional factors shall be recorded as well.

It is recommended to discuss EMI noise mitigation measures on instrumentation signals with the testing facility. For example, shielded cable is recommended for analogue signals runs with the cable shield connected to the DAQ ground on the DAQ end.

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.

If signals are required for real-time feedback control (e.g. force or torque feedback), they should be recorded sufficiently fast to minimize control phase delays. For Stages 1 and 2, feedback control signals should be acquired at no less than 500 Hz. For Stage 3, feedback control signals should be acquired at no less than 200 Hz.

NOTE The appropriate data acquisition rate can 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 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 signals should be recorded and synchronised on a common time base. This can be achieved by using the same DAQ system, although care should be taken that signal pre-conditioning does not introduce an excessive phase lag. Where implementing a common time base from a master clock (e.g. GPS time stamps) is not practical (e.g. due to hardware limitations) a common start trigger shall be used for synchronisation. In this case, a means of quantifying clock drift should be incorporated, such as a common periodic signal (e.g. sine wave) recorded on the individual DAQ systems.

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) might misalign samples. This should be checked during testing to obtain an estimate of inaccuracy.

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.
- PTO control settings.
- 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.
- A descriptive identifier associated with any model change, e.g. mooring angle, mooring spring stiffness, etc.

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 calibration factor is the relationship between the recorded signal unit (for example voltage) and the actual physical quantity (for example force). Calibration factors for all sensors shall be documented.

8.9 Instrument response functions

In special cases, instrument response functions or compensation factors of non-ideal test conditions might 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 or DAQ issues shall be clearly documented.

8.11 Special 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.

It is recommended to rely on industrial grade, off-the-shelf hardware for the WEC SCADA system. Such systems are readily available and enable deterministic control and data acquisition. Low-latency, low-jitter real-time digital fieldbus communication for control and feedback signals is recommended wherever possible.

NOTE Control theory and control algorithms might not have changed substantially in recent decades, but the way in which they are computed has. Digital real-time control on industrial grade computing systems is now industry best practice for new designs.

The control algorithm for power absorption control commonly only represents a small fraction of the code implementation required for the overall SCADA system. It is recommended to commence the design process for (i) the overall safety system; (ii) any required state machines, and (iii) control of auxiliary systems (e.g. fans, cooling circuits, load management system) well-ahead of the ocean deployment. It is also recommended to test any auxiliary system controls as part of the Stage 3 bench testing process in addition to the PTO bench testing outlined in 5.5.4.

The safety control system for a Stage 3 device is likely complex, and it is recommended to undertake a Failure Mode and Effect Analysis to aid the development of the safety system. The system should be fault tolerant, such that the overall control system is not susceptible to a single point of failure.

Once all controls (absorption controller, safety controls, auxiliary controls) have been integrated into a single system, their overall real-time computation might be significantly more burdensome on the computing hardware from when they operated in isolation during testing. It is hence recommended to undertake the control system integration as early as possible, and to allow sufficient computing headroom on the real-time control platform.

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.

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 dimensions (length, width, etc.) of the WEC profile to approximate commercial-scale design. Constrained DoF testing allowed.	Major dimensions (length, width, etc.) of the WEC profile to match commercial-scale design as closely as possible.	All aspects of the WEC profile to match commercial-scale design as closely as possible.
Mooring	Full layout (footprint) not essential.	The principle of the mooring to WEC interface should be similar, while the similitude of the full layout (footprint) is not essential.	All dominant properties required and scaled to match commercial-scale 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 commercial-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 approximate commercial-scale design.	Properties proportional to distances, and scaled pre-tension scaled to match commercial-scale design as closely as possible.	All relevant dominant properties scaled to match commercial-scale design as closely as possible.

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.	A mechanism should be used that will result in a representative and fully modellable response.	Exact mechanical equivalent in type and scaled to match prototype parameter.
Generator	PTO implementation: friction based or linear with velocity. Quadratic if an orifice plate is used.	PTO implementation: Friction based, linear or non-linear with velocity or PI, PID, MPC.	Exact generator equivalent in type and scaled to match commercial scale parameters.
Controls	Simplified controls; Coulomb or linear damping.	Controls equivalent in operation; however, aspects relating to time within the algorithms might require special treatment due to scaling. Can be Coulomb, ideal linear, higher order 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 (1:30 scale) to 0,1 W (1:100 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 commercial-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 though a control system.

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

See 4.5 for additional Stage 3 PTO and control system requirements.

9.4 Physical measurements

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 physical 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[a].
Dynamics	All DoFs contributing to absorbed power.	All DoFs contributing to absorbed power.	All DoFs contributing to absorbed power at each conversion stage[a].

[a] 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.

Since multiplication between different quantities is required during the post processing, all power performance signals shall be recorded such that they can be fully time synchronised.

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.