# IEC TS 62600-202

Edition 1.0  2022-04

# TECHNICAL SPECIFICATION

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inside

**Marine energy – Wave, tidal and other water current converters –**
**Part 202: Early stage development of tidal energy converters – Best practices and recommended procedures for the testing of pre-prototype scale devices**

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and recommended procedures for the testing of pre-prototype scale devices

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

## Part 202: Early stage development of tidal energy converters – Best practices and recommended procedures for the testing of pre-prototype scale devices

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IEC TS 62600-202 has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters. It is a Technical Specification.

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

| Draft | Report on voting |
|---|---|
| 114/407/DTS | 114/414A/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.

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.

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.

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- withdrawn,
- replaced by a revised edition, or
- amended.

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## INTRODUCTION

To further develop the tidal energy industry, Stage Gates, best practices and recommended procedures for the testing of pre-prototype scale devices must be well understood. This document is a collaborative effort from technology developers, academic researchers and test facility managers.

The purpose of this document is to provide a structured approach in testing and evaluating Tidal Energy Converters. By following a standardised design path, risk will be reduced and stakeholder confidence increased. Through best practise guidance and applicable methodologies this document will ensure consistent, appropriate and comparable data is collected for the characterization and analysis required in the development of a Tidal Energy Converter. Furthermore, the reporting procedures will ensure that the results can be replicated by others.

The core of this document follows a Stage Gate approach; for each stage the program of work is outlined and supporting information relating to test planning and reporting presented. The specific recommendations are provided in a holistic manner guiding the process with respect to test planning, reporting requirements, data acquisition, test environment characterization, and characterization of both rotor and device (motion) performance. Annexes provide the reader with further information on facility selection and instrumentation.

The overall goal of this document is to accommodate the majority of technology developers and facilitate a coherent and structured approach that will accelerate the tidal energy sector in fulfilling its market potential as a renewable energy contributor. However, it is recognised that this document will not cover every eventuality that may be relevant for all users. Therefore, this document assumes that the user is familiar with the subject matter and has access to, and reviews relevant literature, including the literature cited herein.

NOTE  This document presently does not describe testing under wave-current interaction, effects of turbulence on tidal energy converters beyond a basic introduction to some turbulence parameters typically reported, and quantification of uncertainty which is covered in other referenced documents.

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

## Part 202: Early stage development of tidal energy converters – Best practices and recommended procedures for the testing of pre-prototype scale devices

## 1   Scope

This document specifies the development stages of Tidal Energy Converters up to the pre-prototype scale (Stages 1 to 3). It includes the hydraulic laboratory test programs, where environmental conditions are controlled so they can be scheduled, and the first scaled system open-water trials, where combinations of tidal currents, wind and waves occur naturally and the programs are adjusted and flexible to accommodate these conditions. Full-scale prototype (Stages 4 and 5) development is not covered in this document.

This document describes the minimum test programs 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:

a) Planning an experimental program, including a design statement, technical drawings, selection of scale and facility based on physical laws, site data and other inputs;

b) Device representation and characterization, including the physical device model, power-take-off components, foundation and mooring arrangements where appropriate;

c) Energy resource and environment characterization, concerning either the tank testing facility or the open-water deployment site, depending on the stage of development;

d) Specification of explicit test goals, including power conversion performance and device loads.

Guidance on the measurement sensors and data acquisition packages is included, but not dictated. Providing that the specified parameters and tolerances are adhered to, the device developer is free to select the components and instrumentation.

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

It is anticipated that this document will serve a wide audience of tidal energy stakeholders, including device developers and their technical advisors; government agencies and funding councils; test centers and certification bodies; private investors; and environmental regulators and non-governmental organizations.

## 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: Vocabulary*

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

IEC TS 62600-103:2018, *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 62600-200, *Marine energy – Wave, tidal and other water current converters – Part 200: Electricity producing tidal energy converters – Power performance assessment*

IEC TS 62600-201:2015, *Marine energy – Wave, tidal and other water current converters – Part 201: Tidal energy resource assessment and characterization*

IEC TS 62600-300:2019 *Marine energy – Wave, tidal and other water current converters – Part 300: Electricity producing river energy converters – Power performance assessment*

ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

ISO/IEC 17025:2017, *General requirements for the competence of testing and calibration laboratories*

# 3   Terms and definitions

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

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

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

**3.1**
**blockage**
<of a tidal energy converter under test in a specific test facility> ratio of the tidal energy converter projected area to the facility test section cross-sectional area

Note 1 to entry:   There is a constraining effect exaggerating performance data when this ratio is too high, which is typically observed for ratios greater than 5 %.

**3.2**
**Stage 1**
small-scale testing in the laboratory

Note 1 to entry:   Stage 1 is equivalent to Technology Readiness Level (TRL) 2-3.

**3.3**
**Stage 2**
medium-scale testing in the laboratory

Note 1 to entry:   Stage 2 is equivalent to Technology Readiness Level (TRL) 4.

**3.4**
**Stage 3**
large-scale testing in open water

Note 1 to entry:   Stage 3 is equivalent to Technology Readiness Level (TRL) 5-6.

**3.5**
**turbulence intensity**
<in a tidal flow> ratio of the tidal current speed standard deviation to the mean tidal current speed.

Note 1 to entry:   It is also referred to as turbulence level, and is a very simplified description of how turbulent the flow at a tidal site or in a facility is.

Note 2 to entry:   Turbulence intensity is to be determined from the same set of measured data samples of tidal current speed, and taken over a specified period of time.

## 4    Symbols and abbreviated terms

| | |
|---|---|
| ADCP | Acoustic Doppler Current Profiler |
| ADV | Acoustic Doppler Velocimeter |
| AEP | Annual Energy Production as defined in IEC TS 62600-1 |
| AD | Analogue to Digital |
| CoG | Centre of Gravity |
| COTS | Commercial off-the-shelf |
| DAQ | Data Acquisition |
| DoF | Degrees of Freedom as defined in IEC TS 62600-1 |
| EEP | Energy Extraction Plane as defined in IEC TS 62600-1 |
| FMECA | Failures Mode, Effects and Criticality Analysis |
| MLW | Mean Low Water |
| MHW | Mean High Water |
| PDF | Probability Density Function |
| RAO | Response Amplitude Operator |
| PTO | Power-Take-Off as defined in IEC TS 62600-1 |
| SCADA | Supervisory Control and Data Acquisition System |
| TEC | Tidal Energy Converter as defined in IEC TS 62600-1 |
| TEOS-10 | The Thermodynamic Equation of Seawater – 2010 |
| TRL | Technology Readiness Level |
| TSR | Tip Speed Ratio |
| ULS | Ultimate Limit State in the context of structural engineering |

## 5    Staged development approach

### 5.1    General

This clause introduces the staged development approach to the design and evaluation of a TEC through physical model testing. Each stage of development is motivated by risk reduction. The primary goals for each stage address elements that should be completed before proceeding through the user's pre-defined Stage Gate for that stage. Each stage corresponds to technology readiness levels (TRL) that measure the progress of technology advancement.

Scaled tidal flow conditions produced in the test tank should be representative of anticipated full-scale tidal flow conditions at the expected deployment sites; namely depth-limited turbulent open channel flows, such as those produced in large flumes. Departures from these conditions due to test facility limitations or differences, e.g., absence of velocity gradients, ambient turbulence and other unsteady flow characteristics over the energy extraction plane, for example in towing tanks, should be documented, and the anticipated effects on test results should be described.

Table 1 shows an overview of the Stage Gate framework and process from the early design concept to the deployment of the first limited device number array, Stage 1 to 5. For each Stage Gate, Table 1 includes the relevant model-test description, typical geometric scale range, test objectives, and Stage Gate success metrics used in the go/no-go analysis.

This Stage Gate framework is designed to be consistent with TEC development and evaluation guidance and protocols developed by the International Energy Agency, Ocean Energy Systems (IEA OES) under Annex II (Bahaj, Blunden, and Anwar 2008; Nielsen 2010).

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 TRL 1 to 6. Stages 4 and 5 concern full scale (or near full scale) testing and are not covered in this document.

This document does not dictate a scale for each of the Stages 1-3. The model testing scale heavily depends on the test objective, size of full-scale TEC, governing scaling laws to achieve dynamic similitude, and the fidelity of the available instrumentation. The scales provided in Table 1 are included as indicators based on previous TEC development efforts.

Every type of TEC will have slightly different requirements so a customized program should be drawn up around these basic testing requirements. Different physical models may be prepared to evaluate specific subsystems or design features. The necessary and recommended goals and experimental activities for Stages 1 to 3 are described in detail in Clauses 6 through 13. Activities are to be defined in the context of best engineering practice, where factors of safety, reliability or other design philosophies are followed.

A Stage Gate process shall be applied after each set of trials to evaluate if the TEC has achieved the required experimental objectives before advancing to the next stage.

A set of Stage Gate criteria for the evaluation of the TEC response and performance at the end of each testing period are defined for Stages 1 to 3 in 5.2 to 5.4. These criteria shall be addressed before advancing to the next stage. These criteria (5.2 to 5.4 ) are currently 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 would be required to optimize its 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.

**Table 1 – Staged development approach**

| Stage | Model test description | TRL | Typical range of scales | Test objectives | Go/No-Go analysis Stage Gate success thresholds |
|---|---|---|---|---|---|
| 1 | Concept model | 2-3 | 1:15-100 | Concept verification: Turbine rotor: Demonstrate power energy conversion Platform: Test initial design choices and select most favorable design configuration. Characterize design loads and motions for operational reliability and survival. | Rotor power conversion demonstrated. Loads characterized for normal operating and extreme conditions. A favorable design configuration is found. |
| 2 | Design model | 4 | 1:3-10 | Design verification: Demonstrate power performance and survival in simulated tidal flow environment at a physical scale that minimizes scale effects (chord Reynolds number dependency). Demonstrate component PTO. Demonstrate other component or subsystem, e.g., controls. | Power performance equals or exceeds target based on numerical model. Loads characterized for normal operating and extreme conditions. PTO operates as designed and at expected efficiency. Control or other subsystem operates as designed. |
| 3 | Subsystems model | 5-6 | 1:1-5 | Sub-system model verification: Assess energy production in real tideways. Demonstrate subsystem integration. Fully operational TEC tideway trials. | Power performance equals or exceeds target based on numerical model. Loads characterized for normal operating conditions. PTO operates as designed and at expected efficiency. Control or other subsystem operates as designed. |
| 4 | Solo-device proving – near to full scale testing of prototype device. | 7-8 | 1:1-2 | Technical/operational evaluation of near-full size to full size power plant deployment. Advance pre-production to pre-commercial unit. | Operations analysis: Demonstrate operability, maintainability, access, health and safety. |
| 5 | Multi-device proving – Commercial demonstrator tested at sea for an extended period. | 9 | 1:1 | Economic evaluation of final commercial unit. Small farm trials, 3-5 units. | Economic analysis: Demonstrate levelized cost of energy (LCOE) target met. |

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

a) Analysis of the results from the appropriate preceding test program;

b) A comparison with the related TEC design statement produced at the beginning of the stage;

c) An overall design review, preferably by a third party, independent, established engineering company.

The review shall follow the same set of evaluation criteria at each stage which are based on the test goals specified for each stage. As the test article physical scale increases, the complexity of the model and trials increases to generate more accurate results with less uncertainty in the prototype extrapolation. The Stage Gate evaluation criteria reflect this decreasing uncertainty.

The evaluation criteria shall include:

d) Energy conversion;

e) Device (platform) seakeeping (motions) if applicable;

f) Support structure loads;

g) Mooring loads if applicable;

h) PTO loads;

i) Ultimate Limit State (ULS) verification.

It is recommended that the physical model testing is performed in conjunction with a mathematical model development, and the above criteria can also be used for the validation of this mathematical model. In this context "mathematical model" includes analytical and numerical models.

NOTE   See also Annex A for an informative description of the Stage Gate process.

## 5.2   Stage 1

### 5.2.1   Scope

Stage 1 is intended to demonstrate that the TEC design concept has potential and may be realized or transitioned up to TRL 3. A key purpose of Stage 1 testing is to explore initial design choices. A full description of each design should be provided, including concept descriptions for the subsystems, a list of their major components, and documentation for standard, commercial off-the-shelf (COTS) components used within their specification and not requiring further testing (Bahaj, Blunden, and Anwar 2008).

Stage 1 should also identify research and development requirements for Stages 2 and 3, in addition to the minimum requirements specified below.

At Stage 1, a detailed design for the full-scale prototype is not required, and Stage 1 is often used to explore alternative device configurations.

There are four facets to Stage 1 tests:

a) Proof of concept: To verify that the device design concept operates under idealized tidal flow conditions as predicted and described (under TRL 1);

b) Optimization of design: to evolve the most favorable device configuration(s);

c) Device performance: To obtain a first indication of power performance for the optimized PTO setting of the device;

d) Survivability check: To introduce extreme conditions to observe device response in survival conditions, and to investigate device-specific failure modes.

All four facets are required to provide input to Stage Gate 1. For the proof of concept phase of Stage 1, the testing may rely on an idealized physical model.

The PTO may be represented by a simplified mechanism. The selected PTO mechanism shall provide a damping/load that may be characterized across an appropriate range of settings.

For seakeeping testing of a platform, the thrust load of turbine rotors shall be represented. These loads should be verified, ideally under the same test conditions, but may be verified in other experimental campaigns by using a mathematical model.

The methodology of testing recommended here follows the best practice for Stage 1 testing and builds upon the practices developed in Tidal-current Energy Device Development and Evaluation Protocol (Bahaj, Blunden, and Anwar 2008). The results of this stage are lessons used to converge on a full-scale design and data to be validated in the next stage.

### 5.2.2   Stage gate

• Energy conversion appraisal shall be based on power capture prospects estimated from selected steady uniform currents.

- Support structure appraisal shall be based on the time series and associated analysis of the support loads.

- Seakeeping appraisal (if required) shall be based on the response-amplitude operator (RAO) for the dominant or relevant degrees of motion.

- Mooring appraisal (if implemented) shall be based on the time series and associated analysis (e.g. RAOs) of the mooring line loads.

## 5.3 Stage 2

### 5.3.1 Scope

The purpose of the Stage 2 testing is to fully validate the TEC design changes as a result of testing in Stage 1. Stage 2 testing can be associated with a significant amount of design variables, particularly in the rotor description or platform design, but shall be based on similar performance indicators as adopted during Stage 1.

Stage 2 testing shall specifically address the following key objectives:

a) Stage 1 validation: To validate the technical conclusions drawn from the previous test program and to identify potential scaling issues between the two stages;

b) Device performance: To verify the energy conversion performance;

c) Device or platform dynamics and kinematics are verified;

d) Survivability check: To introduce extreme conditions to observe device response in survival conditions, and to discover device-specific failure modes;

e) The largest scale feasible for the available facilities should be used to reduce the influence of scale effects, following Reynolds number and blockage criteria outlined in Clause 6;

f) If applicable and practical the flexible umbilical electrical cable should be incorporated in selected tests;

g) Mooring function check: To verify the proposed full-scale mooring and anchorage system design, if applicable, and to assess a realistic mooring response.

It is expected that turbine rotors and platforms be tested at different scales in Stage 2. For a turbine rotor, it is recommended that Stage 2 testing incorporates an advanced turbine blade and rotor simulation, exhibiting an accurate representation of the proposed full-scale unit, and introducing a rotor control mechanism by which control strategies can be evaluated. For a platform, Stage 2 testing may still benefit from representative turbine rotor loads acting on a structure.

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

For validation of the Stage 2 results, both the tidal environment and the device parameters should be as close as possible to those adopted during Stage 1, adjusted to the Stage 2 scale. A representative set of conditions should be included, including a range of steady flow conditions with waves. In selecting these conditions, the range of each parameter (mean current speed, ambient turbulence level and PTO damping/breaking) that supported the main Stage 1 conclusions should be documented. The medium-scale model may have to be idealized 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.

### 5.3.2 Stage gate

Energy conversion and device loading appraisal shall be based on the power curve for a range of tip speed ratios and power capture for a minimum of 3 tidal current speeds and demonstrating Reynolds number independence of performance if applicable.

Seakeeping appraisal, if applicable, shall be based on the RAO for the dominant or relevant degrees of motion.

Mooring appraisal, if applicable and implemented, shall be based on the time series and associated analysis of the mooring line loads.

NOTE   At Stage 2, the mean annual energy production (AEP, in kWh) can be estimated by combining an appropriate TEC 'power curve', derived as described in IEC TS 62600-200, with the tidal energy resource data describing the temporal distribution of the current velocity at the intended TEC deployment location (see 8.3 of IEC TS 62600-201:2015). This type of approach more accurately determines the performance and limits the uncertainty.

## 5.4  Stage 3

### 5.4.1  Scope

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

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

- Structural check: between Stage 2 turbine rotor tests, combined with Stage 2 platform or support structure tests;

- 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;

- Survival mode check: to verify failure mitigation strategies;

- Galvanic corrosion check: Using alloys and composites representative for the future prototype, to monitor the model for symptoms of galvanic corrosion or stress corrosion cracking;

- Fatigue (cyclic) stress evaluation: To install sensors at locations where cyclic stresses may determine system life;

- If applicable monitor for adverse effects due to biofouling, debris, cavitation or sediment interaction.

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

The test site and scale should be matched in deployment depth, current speed, waves and any other parameters that affect the device and its subsystems.

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

### 5.4.2  Stage gate

The Stage Gate in this case includes:

- The evaluation/verification of the turbine rotor/PTO efficiency and control;

- The evaluation/verification of risk and safety management;

- The evaluation/verification of the power performance curve;

- The evaluation of installation and maintenance procedures and durations;
- The evaluation of fabrication methodology and cost;
- The evaluation of platform motion, support structure loads, and mooring loads, if applicable;
- The evaluation of device survivability.

NOTE   Where possible, verifications can be undertaken before open ocean trials commence. For example, the PTO efficiency and control may be evaluated before final device fabrication in a test-stand setup.

## 6   Test planning

### 6.1   TEC similitudes

#### 6.1.1   General

When physical relationships are described in terms of dimensionless ratios found from dimensional analysis or directly from the governing equations, e.g. ratios of significant forces, then model test data can be extrapolated to prototype conditions by equating these dimensionless ratios. In addition, similarity considerations can be applied to turbine performance data from a certain type of machine under certain operating conditions; and used to predict performance characteristics of the same machine, or of a geometrically similar machine, under different operating conditions. Further, similarity considerations provide a means of cataloguing machine types and thus aid in the selection of the type suitable for particular conditions (Arndt, Arakeri, and Higuchi 1991).

The correct implementation of small-scale testing of a TEC device, beyond proof of concept, requires a fundamental understanding of the underlying physics governing operation of the device, and the appropriate similarity principles used in model scaling. The choice of governing similarity parameters can be dependent on device type and location. Key similarity parameters used in governing the operation and scaling of devices should include:

Reynolds number (Re): Reynolds number scaling is one of the key scaling relationships to consider for model testing of tidal turbines. It is dealt within 6.1.2.

Froude number (Fr): This should be considered when evaluating the performance of shallow depth, floating, or mid-water TECs in a wave-current environment. Froude number should also be taken into consideration when free surface deformation due to the presence of the turbine is *not* negligible.

Strouhal number (St): The Strouhal number is used to parameterize unsteady flows in which periodical phenomena can be identified with a representative frequency, such as oscillating foil-type TEC, or unsteady flow induced by TEC support structures.

Cavitation number (σ): Cavitation inception, breakdown and collapse on a surface may have an impact on device performance, radiated noise and surface damage. Appropriate small scale testing should incorporate cavitation modeling when full-scale operation may be susceptible to cavitation. The correct scaling of cavitating flow phenomena at small scale requires tests to be performed in dedicated facilities where pressure can be controlled independent of velocity.

Tip-Speed ratio ($\lambda$): The tip speed ratio is defined as:

$$\lambda = \frac{\omega R}{U} \tag{1}$$

where

$\omega$ is angular velocity of the turbine rotor,

$R$ is the turbine rotor radius, and

$U$ is the freestream flow velocity.

Tip-speed ratio is an important kinematic scaling parameter for rotating turbo-machines such as turbines, pumps and propellers. The inverse of tip-speed ratio is proportional to the corresponding kinematic parameter (advance ratio) used for screw propellers. The scaled

performance of rotating turbo-machines is strongly dependent on matching the full-scale tip-speed ratio while maintaining sufficiently high Reynolds number magnitudes. This requirement typically dictates a minimum model size, above which the TEC performance does not, or at least not strongly, depend on Reynolds.

Other parameters: In unsteady flow, the Current Number ($m$) and the reduced frequency ($k$) are also important. If TEC turbine blades are sufficiently close to the water surface to cause surface vortices, in severe cases with air entrainment (not to be confused with cavitation) then an additional dimensionless circulation parameter, $UL/\Gamma$, where $\Gamma$ is the circulation contribution to the free surface vortices, shall be considered.

Table 2 provides a summary of the scaling considerations.

**Table 2 – Scaling considerations**

| Element | Scaling | Parameters | Application |
|---|---|---|---|
| Turbine rotor | Reynolds,kKinematic scaling | Blade chord, TSR | Power, thrust |
| Fixed support structure | Reynolds, Strouhal | Principle length (diameter, chord) | Loading, vortex induced vibration (VIV) |
| Floating support structure | Froude, Reynolds | Geometry, inflow velocity | Loading, dynamics, VIV |
| Mooring | Strouhal, Reynolds, Froude | Geometry, inflow velocity | Loading, dynamics |
| PTO simulator | Kinematic scaling | TSR, mechanical power | Power |
| Near-field wake | Reynolds, kinematic scaling | Blade chord, TSR | Velocity deficit/ recovery |
| Far-field wake | Reynolds, Froude | Turbine rotor diameter, inflow velocity | Environment, array spacing |

It can readily be shown that Reynolds and Froude number similarity cannot be satisfied simultaneously (for the water at ambient temperature). Scaled tidal tests can typically be designed with sufficient submergence (distance to free surface) so that there is little effect of the free surface. In the absence of waves, only Reynolds number and tip speed ratio similarity as discussed above will be considered for the turbine rotor performance.

NOTE 1   Inaccuracies may be introduced through Reynolds, structural, and power conversion chain non-similitudes for the TEC, and geometric and hydrodynamic non-similitude for the platform, and mooring if applicable. 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 Reynolds scale factor decreases and as the testing progresses in stages, the uncertainty and inaccuracy of scale-up decrease.

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

## 6.1.2   Reynolds scaling

The Reynolds number associated with the interactions between the flow and turbine blades is often referred to as the chord based Reynolds number, $Re_c$ where the length parameter used in its calculation is the turbine blade chord, $c$. It characterizes the flow regime around the hydrofoil and hence defines turbine blade pressure distribution, lift and drag. The velocity parameter for calculating $Re_c$ is not the free stream velocity $U_0$ but the relative velocity $U_{rel}$ experienced by the turbine blade as the turbine rotor rotates, which can be approximated by the vector addition of approach velocity ($U_0$) and the (negative) turbine blade tangential velocity ($\omega r$). The chord based Reynolds number is defined as:

$$Re_c \equiv \frac{\rho U_{rel} c}{\mu} \tag{2}$$

Where $\rho$ and $\mu$ are fluid density and dynamic (absolute) viscosity, respectively.

Attention should be paid to rotors that are designed to highly deflect or untwist under load.

NOTE   The local relative velocity $U_{rel}$ experienced by an axial-flow turbine blade can be calculated more accurately by including the effects of axial induction (subtracted from $U_0$) and angular induction (added to $\omega r$) in this vector addition. However, these are often not known a priori, hence this approximate calculation is used.

For a cross-flow turbine, $U_{rel}$ varies with azimuthal position $\theta$ of the blade with values in the range $U_{rel} = \omega R \pm U_0$(neglecting slowing of the flow as it passes through the turbine rotor, or axial induction), where $\omega$ is the turbine rotational speed and $R$ is the rotor radius. The relative velocity for the turbine blade of a cross-flow turbine, neglecting induction, is given as:

$$U_{rel} = U_\infty \sqrt{1 + \lambda \cos \theta + \lambda^2} \tag{3}$$

For an axial-flow (horizontal axis) turbine chord-based Reynolds numbers should be calculated based on the relative velocity experienced by the turbine blade profile at a given radius $r$ from the turbine rotor axis. The relative velocity for the turbine blade of an axial-flow turbine, neglecting induction, is given as:

$$U_{rel} = U_\infty \sqrt{1 + \lambda^2 \left(\frac{r}{R}\right)^2} \tag{4}$$

For high tip speed ratios and larger values of $r$ the relative velocity can be approximated as $U_{rel} \approx \omega r$. When specifying chord-based Reynolds number for axial-flow turbines, the considered radius shall be specified (a typical value is 70 % of the turbine rotor radius). (Gaurier *et al.* 2015; ITTC 2002).

$$Re_{c_{pr}} = \frac{c_{pr}\sqrt{U_\infty^2 + (0,7R\,\Omega)^2}}{v} \tag{5}$$

Where $pr$ is the % radius and is typically 70 % as shown in Gaurier *et al.* 2015 and ITTC 2002.

In general, for a given hydrofoil section, a lower chord Reynolds number corresponds to a reduction of the peak value of lift to drag ratio and a reduction of the stall angle. As a consequence, the testing of a hydrofoil based device at too low a chord based Reynolds number often results in underestimated energy conversion efficiencies of the device with lower measured power capture. A limiting factor in achieving critically high chord-based Reynolds number in small scale testing of TEC devices, through the increase of flow velocity and angular velocity, would be the onset of cavitation. Thus Reynolds number strict similitude can rarely be achieved, especially with small models and in combination with kinematic similarity (similar tip-speed ratio as explained above). However, a critical threshold value for the Reynolds number shall be exceeded to ensure that the turbine operates in the right flow regime to capture the essential turbine physics. It is recommended that, where possible, higher TRL tests be performed at chord based Reynolds number above a critical value of 500 000. This critical value of Reynolds number can be dependent on turbine type and turbine blade design and may range from 200 000 to 500 000 and thus testing could be performed at lower values if so indicated. Where geometric similitude testing is carried out at lower Reynolds number, developers shall demonstrate asymptotic behavior of results with Reynolds number by varying Reynolds number whilst holding tip speed ratio constant.

Figure 1 and Figure 2 provide an example of the Reynolds dependency of power and drag (thrust) coefficients, in this case for a cross-flow (vertical) axis turbine (US DOE Reference Model 2). Figure 1 shows that the power coefficient depends more strongly on Reynolds number than the drag (thrust) coefficient, both defined in Clause 10. For the Reynolds number range investigated, the power coefficient does not become independent of Reynolds number for this turbine, but is seen to be only weakly dependent on Reynolds number for $Re_c > 200\,000$. Figure 3 shows performance data for a different, higher-solidity turbine. For this turbine, it can be seen that the power coefficient *does* become independent of Reynolds number for $Re_c > 200\,000$.
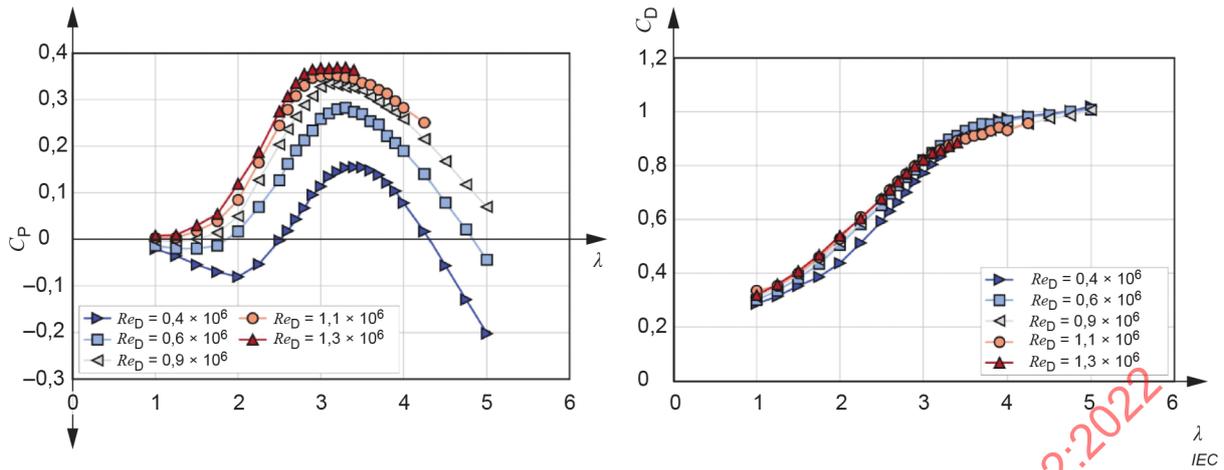
**Figure 1 – Power and drag (thrust) coefficients for the US Department of Energy's Reference Model vertical-axis cross-flow turbine (RM2) tested in a towing tank (Bachant *et al.* 2016)**
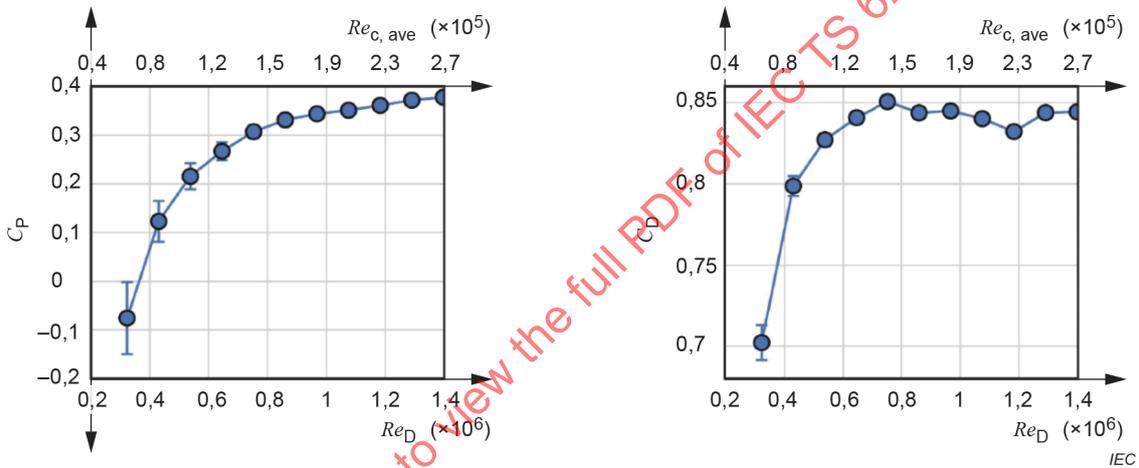


**Figure 2 – Effect of Reynolds number on performance – Power (left) and thrust (right) coefficient for reference model RM2 at $\lambda$ = 3,1 plotted versus turbine diameter and approximate average turbine blade root chord Reynolds number (Bachant *et al.* 2016)**
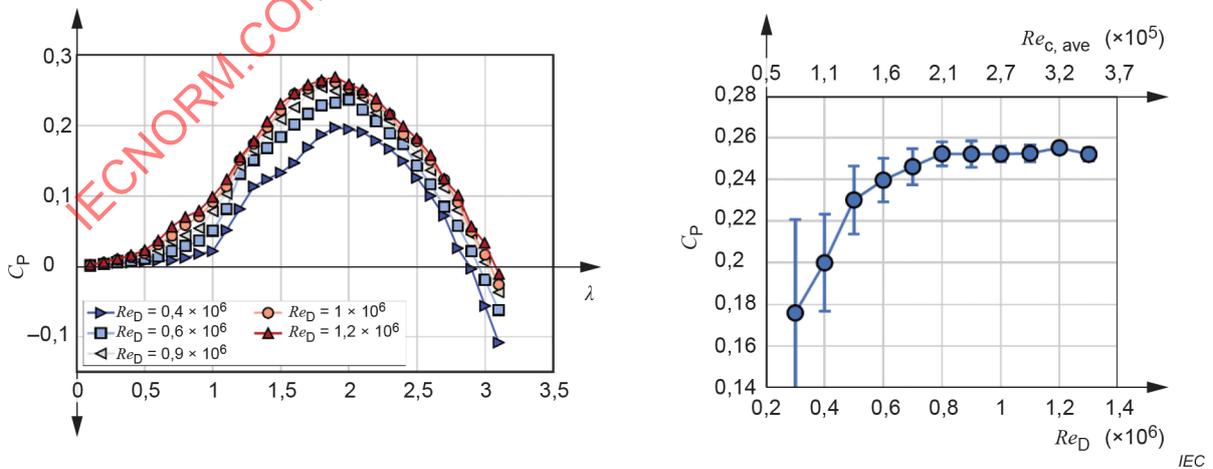


**Figure 3 – Effect of Reynolds number on performance – Power coefficient versus tip speed ratio (left) and power coefficient at $\lambda$ = 1,9 plotted versus turbine diameter and approximate average turbine blade root chord Reynolds number (right), both for UNH-RVAT turbine (Bachant and Wosnik 2016)**

When chord-based Reynolds numbers are not high enough to reach Reynolds number independence, modified hydrofoil shapes may be required to develop similar turbine blade or turbine rotor characteristics to the prototype. If turbine blade profiles are modified to compensate for low Reynolds number effects the blade design process and final blade design shall be clearly documented.

### 6.1.3    Temperature and salinity effects on Reynolds number

The thermo-physical properties of water change with temperature and salinity. These should be considered when reporting Reynolds numbers. Temperature has the most pronounced effect on viscosity, and hence on Reynolds number. Over the range of 0 to 225° C the absolute viscosity of water can vary on the order of 100 % due to temperature, and hence Reynolds number can vary by a factor of two, whereas over the range of 0 to 35 ppt salinity absolute viscosity can vary on the order of 10 % due to salinity (Sharqawy, Lienhard V, and Zubair 2010; Nayar et al. 2016; Intergovernmental Oceanographic Commission 2010; Park and Olivieri, n.d.). Temperature (for all Stages) shall be recorded and salinity (where applicable) should be recorded and any fluctuation reported during the tests. See 9.7 for additional information.

### 6.2    Power take off (PTO) similitude

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

The PTO is made up shafts, linkages and generators, storage, 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.

A specific goal of the Stage 3 testing is to implement a scaled PTO. 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) characteristics are often used. However, these representational PTOs can introduce artificial effects, like stiction, or non-physical hysteretic effects. Further, these representational PTOs may not be able to imitate limitations that will exist in the prototype, such as maximum forces or slew rates from the generator.

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

The ability to mimic the prototype control strategy at model scale is very important. The adverse impact of control strategy between Stage 2 and Stage 3 experimental testing was demonstrated by Frost *et al.*, 2018. 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 prototype's dynamic-kinematic characteristics. It is recommended that PTO control strategy investigation are not undertaken until Stage 2 is reached.

NOTE   Commonly the efficiencies associated with each component of the PTO 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.

For scaled turbine rotors, special considerations shall be given to the uncertainty of the scale-up since the turbine blades rely on hydrodynamics which is fundamentally governed by Reynolds scaling. For more information refer to Clause 10.

### 6.3    Design statement

A design statement shall be available prior to device testing.

For Stage 1, laboratory testing programs the design statement

Shall include:

• Clear statement of the testing goals.

- Technical drawing of the experimental device indicating the anticipated scaling factor to full scale.
- Description of the experimental support structure, platform and/or mooring system (if applicable) and its anticipated functionality.
- Supporting calculations to provide approximate device physical properties and behavior.

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 TECs.
- Literature review of similar systems.

For Stage 2 laboratory testing programs the design statement:

Shall include:

- Clear statement of the testing goals.
- Technical drawing of the preliminary device design in anticipated full scale and the experimental design at model scale.
- Definition of the anticipated full-scale turbine rotor and its characteristics.
- Supporting calculations to provide approximate device physical properties and behavior.
- Technical drawing of the preliminary support structure, platform and/or mooring system (if applicable).
- Characteristic site conditions for the anticipated device deployment location, including typical current velocity, turbulence intensity, wave period, water depth and significant wave height.

Should include:

- A description of any mathematical model of a device, 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 TECs;
- Literature review of similar systems.

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

- Clear statement of the testing goals;
- Technical drawings and construction procedures relating to the TEC;
- Technical drawings of the support structure and/or mooring design;
- Control strategies including set point parameters and process variables;
- Characteristic site conditions for the device deployment location, including typical current velocity, wave period, turbulence intensity, water depth and significant wave height. Additionally, an estimate of the anticipated deployment length needed to sufficiently meet the testing goals;
- Characteristic site conditions relevant to understanding system corrosion including conductivity and temperature;
- Installation procedures;
- Operations and maintenance procedures;

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

## 6.4    Facility selection and outline plan

### 6.4.1    General

Facility selection depends on many criteria which take into account both the test requirements and the facility characteristics. 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.

The facility shall be capable of producing appropriately scaled flow environment at the chosen scale. Particular attention should be paid to Reynolds number that can be achieved, blockage, tip immersion in flume and towing tanks, and proximity to walls.

Where devices are tested in towing tanks, reflections can occur due to the interaction with side walls and the bottom, while blockage effects may lead to different behavior of the model with respect to equivalent operating conditions in an unbounded environment. Well established techniques exist to evaluate effects of blockage for marine vehicles and structures, and hence to correct the measured data. However, these corrections are not as well established for TECs, and caution is advised. Corrections are typically based on the ratio between the cross-section of the model and the cross-section of the basin. This ratio should be reduced as far as possible in order to minimize blockage effects, and in the case of energy conversion devices, to minimize the effect on device performance.

Another consequence of the confined environment is the increased need of a sufficient time interval between successive tests to re-establish still water conditions. The problem may be particularly important when tests are performed in wave conditions.

The blockage ratio shall be reported for each facility used. If blockage ratio exceeds 5 % blockage correction techniques shall be used and reported, if the results are to be used for AEP calculations. Whelan *et al.* present blockage and free-surface corrections for axial-flow devices and propose an approach to correct results in the presence of blockage in conjunction with a free surface (Whelan, Graham, and Peiró 2009). Special consideration should be given if non-axial-flow conditions, common in current turbines, are to be considered (Bahaj *et al.* 2007). Ross and Polagye (2020) provide guidance on the validity of various blockage corrections and found the method of Houlsby and Vogel (2017) which requires the measurement of thrust, to be most accurate. Generally, test conditions where blockage significantly exceeds 10 % should be avoided.

If the TEC model test results are used for numerical model validation, then the same blockage scenario as in the test should be replicated in the model.

### 6.4.2    Stage 1 and Stage 2

The following are useful considerations for laboratory facilities:

- Tank dimensions, minimal blockage effect.

- Directionality of the circulating system.

- Model support/towing structure.

- Wave generation capabilities
    - Wave conditions (height, period and direction).
    - Wavemaker active absorption feedback.
    - Stability of the water level at the wavemaker location.

Stage 2 shall also specifically consider:

- The increased scale of the model and the associated change in facility size.

- Uniformity of the flow field.
    - Type of recirculation method utilized.

- – Flow entry method.
- – Turbulence intensity.
- – Turbulent mixing layers.
- – Boundary layers.
- – Methods of reducing turbulence.
    - • Honeycomb filters.
    - • Guides vane characteristics shape, number, and angle.
- • Wave generation capabilities; combined wave and current interactions.
- • The role of wave-current interactions, particularly in addressing station keeping (if applicable) and mooring loading.
- • The spatial requirements of a realistic mooring system footprint (if applicable).
- • Proper inflow representation and the characterization of the inflow conditions (flow speed, direction, uniformity, steadiness and turbulence characteristics – small and large scale turbulent structures),
    - – blockage and free surface effects.

In the case of turbine rotor or rotor/nacelle testing for axial-flow or cross-flow turbines at the concept design stage (Stage 1), model mounting characteristics, and instrumentation (invasive or non-invasive) of appropriate accuracy to meet test objectives should be used (see Annex B).

Where floating devices are being tested including the effects of the supporting platform, it is naturally beneficial to use a flume or tow tank with a free surface; where wave effects are important, then a flume or towing tank with a wave-maker shall be used.

Conversely for bottom-fixed devices when testing is intended to include the effects of the support structure, a tunnel or flume will offer advantages over a towing tank in ease of installation, and in modelling the effects of the boundary layer over the sea bed on the flow around the supports. The importance of the impact of turbulence on the results obtained, and the turbulence levels achieved in tests in different facility types, should be carefully considered.

Gaurier *et al.* compared the performance of a turbine in four different facilities, two towing tanks and two circulating flumes (Gaurier *et al.* 2015). The variation in results were found to come from the inflow turbulence and blockage effects which were corrected for. More recently, Allmark *et al.* compared the non-dimensional performance characteristics of a turbine at three of the same four facilities as Gaurier *et al*. Similar variations were found and the importance of consistent device setup played an important role in the results comparison (Allmark *et al.* 2020).

Frost *et al.* compared results from a towing tank (equivalent Stage 2) and tidal test site (equivalent Stage 3) using the same experimental turbine and setup (Frost *et al.* 2018). The reported difference was a reduction in power performance of 8 % between the lab and the field and was attributed to the unsteady inflow of the tidal test site.

Each test facility is unique in its capabilities and operation, and experienced operators shall be consulted. To ensure all important parameters are included, a detailed testing plan shall be devised and reported. 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 environmental calibration or characterization (if not already available);
- • Number of individual experimental runs, based upon a definition of:
    - – Number of tidal conditions;
    - – Number of sea states;
    - – Number of device design variables and their range;
    - – Range of inflow current parameters;
    - – Range of regular wave parameters and number of wave spectra;

- Duration of each experimental run;

- 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.

Defining a logical order to any experimental runs shall balance time, component life, device design and sensor performance. Where possible the tests should run in a random order to isolate any long-term drift of sensors. More energetic test environments that result in greater forces and motions are ideally run last in case of a failure.

If a component fails and a like for like replacement is made, a repeat test shall be carried out to verify the system is performing as expected. A benchmark case may be ideal for this purpose.

### 6.4.3    Stage 3

Field tests provide opportunities for device evaluation in a realistic environment with limited control over test conditions and requirement of field instrumentation and methodology. It is recommended that established open ocean trial test centers should be utilized to complete Stage 3. When this is not possible care shall be taken to identify a suitable site. The following points should be considered during the sea zone selection:

- Appropriate water current characteristics

  – turbulence intensity.

  – turbulent mixing layers.

  – boundary layers.

- Appropriate spatial and temporal wave condition in both amplitude and period;

- Appropriate model support/towing structure;

- Appropriate water depth for mooring fidelity;

- Convenient launch and deployment facilities, especially vessels;

- Local service and maintenance amenities;

- Land-based data station;

- Appropriate atmospheric and oceanographic conditions, such as the absence of rip currents, hurricanes or excessive suspended sediment.

- Licensing and consenting from the appropriate authorities

IEC TS 62600-201 should be consulted for unestablished open ocean trial sites.

When the prevailing sea conditions shall be accepted as they occur, it is essential to develop a test program that accommodates loss of control. The survival aspect of Stage 3 testing is sought to achieve conditions that get close to true survival conditions. Example interpretations of such testing conditions include:

a) testing that achieves 80 % of the expected ULS,

b) testing that achieves the worst possible condition within a 1-year period at the Stage 3 deployment location, or

c) an accelerated exposure of the device to high energy seas at a more exposed site with the proviso that destructive seas may also occur at such sites.

Other interpretations are possible and are to be noted in the reporting.

A full test plan shall be produced prior to deployment to ensure all aspects of the design statement are fulfilled. Results shall satisfy the uncertainty criteria specified for each testing goal.

## 6.5 Physical model considerations

### 6.5.1 General

Depending on the stage, TEC model testing may involve the hydrodynamic power performance characterization of only the turbine rotor (mechanical characterization), or a more complete system characterization, including an actual or modelled PTO.

For Stages 1 or 2, TEC model turbines may include only the turbine rotor, i.e., the prime mover consisting of mechanical and/or hydrodynamic components used for converting the kinetic energy in the water to shaft work. In this case a system for loading, controlling, and measuring turbine torque and rate of rotation (RPM) is necessary.

For Stage 3, and sometimes at lower stages, developers may test a complete TEC model or small scale prototype that includes a generator and control system. To characterize turbine rotor performance from the combined performance (efficiency) of the system, the separate efficiency/losses from the other components, i.e., gearbox efficiency, generator efficiency, power conversion efficiency, bearing/powertrain friction, etc., or, alternatively, the efficiency/losses from the balance of the system other than the turbine rotor shall be evaluated.

In all stages the test model, including model components and PTO shall represent the full-scale device to a level of geometric and functional accuracy appropriate to the stage of development. Consideration should be given to hydrodynamic performance, including issues such as surface finish, boundary layer transition, and model stiffness, to ensure that the hydrodynamic and hydro-elastic behavior is representative. For small-scale models achieving adequate geometric accuracy and stiffness can be challenging.

The choice of scale ratio influences model manufacture, instrumentation and equipment and choice of facility.

For Stage 1 tests it may be appropriate to model only the rotor of a turbine, whilst Stage 2 and 3 tests would also require an accurate model of the nacelle and tower.

The chosen model scale shall provide adequate space for the required instrumentation, and model dimensions shall be compatible with the capacity of maximum loads of measuring devices (torque-meters, dynamometers) and provide adequate space for other equipment (slip-rings, motors etc.). Instrumentation shall have a level of accuracy to allow model performance to be quantified appropriately to the TRL of the test.

To ensure high quality measurements from the turbine models, care should be taken to ensure that sensors are configured in a way to measure as directly as possible the physical quantities of interest. In the case of load measurements, this means that transducers should be located as close as possible, in terms of load path, to where the load is applied so that measurements are least affected by the mechanical behavior of other components located in between. As a consequence, force sensors should be located 'upstream' of water seals so that parasitic friction associated with those seals do not affect measurements. If this is not possible, the friction force associated with the seal shall be measured so that it can be subtracted from the overall load measurements.

### 6.5.2 Stage 1

The Stage 1 model construction should consider the following:

- Design to allow individual modification of the key device design parameters;
- Construction material selection (material properties that have a significant impact on the device behavior shall be scaled, otherwise scaling material properties not required);
- The physical model construction enabling accurate measurements of the key parameters;
- PTO simulation using a simplified, yet accurate mechanism, that has been tested before the experiment for operation;
- For floating systems, mooring simulation to match desired device dynamics.

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

### 6.5.3    Stage 2

The medium-scale physical model shall more representative of the full-scale device 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 the Stage 1 suggestions in addition to the following:

- The dynamics of the model should be as close as possible to an exact representation of the full-scale device;

- PTO simulation using representative mechanism capable of exhibiting the proposed full-scale kinematic and dynamic PTO characteristics and control strategy with both aspects experimentally confirmed before testing;

- For floating systems, mooring system will need to meet both geometric and structural similitude, potentially requiring two designs to meet the goals of this stage.

Stage 2 models should be significantly more sophisticated, than Stage 1 models, and all aspects of model fabrication and model handling have to be carefully considered.

### 6.5.4    Stage 3

The size for a Stage 3 scaled model should be based on the tidal parameters found at the deployment/open ocean trial site and be sufficient to accommodate a fully operational tidal turbine, including the PTO and power electronics pack. For devices above a 500 kW rating, this will still be a significant model on the order of several tons and so will require specialized maritime handing. The device will not need to be grid connected and an on-board grid emulator can be used.

The Stage 3 model construction should consider the following:

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

- Identification of ULS loads and factors of safety;

- Identification of key strains within the device structure;

- Accurate and complete assembly procedures;

- Instrumentation needed to record required data streams including sensor redundancy;

- Supervisory control and data acquisition system (SCADA);

- Efficiencies in the power conversion chain;

- Accurate foundation (mooring for floating systems) designs and assembly procedures;

- Deployment procedures;

- Safety of workers during installation and maintenance;

- Construction material selection.

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

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

### 6.5.5    Methods for applying torque

Methods for applying torque (loading) can be separated into three general categories—brakes, generators, and motors. The simplest types of brakes are mechanical, e.g., disk brakes, which rely on friction between two surfaces to generate heat and remove mechanical energy. These can be actuated manually via cable, hydraulic or pneumatic pressure, or by an electrical actuator. Electromagnetic brakes, such as particle and hysteresis brakes produce torque directly from electrical energy.

Generators and motors both impose torque loads by producing electrical energy, but motors have the ability to input positive torque, allowing precise control of tip speed ratio. A motor can also be used to provide purely resistive torque, thereby acting as a generator. Motor types

include AC induction, DC brushless, stepper, and permanent magnet servo (AC or DC). Electrical power can be dissipated through a resistive load, which for some motors is built into the drive or amplifier.

Regardless of the torque loading method employed, it is recommended that rotational speed be controlled and torque load measured, rather than applying a torque load and measuring the resulting rotational speed. This approach is advantageous since typically for a axial-flow axis turbine type non-dimensional power curves, there are two tip speed ratios corresponding to a given torque when operating off maximum power coefficient.

### 6.5.6 Methods for controlling angular velocity

Controlling angular velocity is linked closely with application of load torque. For axial-flow turbines, a steadier hydrodynamic torque is expected compared to cross-flow turbines, which means control requirements are somewhat simpler for axial-flow turbine rotors, though for all turbines tip speed ratio, or RPM, is the main independent parameter varied to observed changes in device performance. Servo motor systems, though typically the most expensive loading method, usually include motors with integral feedback devices and a drive or amplifier with a built-in high-bandwidth, high-accuracy closed-loop speed and position control, providing a convenient all-inclusive speed measurement and control package. Similar results can be achieved with less expensive brush DC or AC induction motors, though speed accuracy and ability to reject disturbances—e.g. the oscillating torque of a cross-flow turbine—are reduced.

## 6.6 Additional test procedures

### 6.6.1 Dry run

It is recommended that a turbine rotor be run dry to check load responses and resonance frequencies.

### 6.6.2 Natural frequency

It is recommended that excitation tests be carried out to determine structural resonance frequencies. This can be carried out by a single impact to a range of components in a range of directions. A light-weight plastic hammer is ideal; however, great care and a light touch are recommended. This action also serves as a good instrumentation and channel check.

## 6.7 Uncertainties and repeat tests

Full scale prediction uncertainty is related to measurement inaccuracy during testing, finite test time, and scale effects. Testing is more accurate with less uncertainty as the scale increases due to the ability to better represent the model and to a reduction in scale effect.

Repeating tests to understand the uncertainty of the experiment for a particular test is useful and as the scale increases it can be used to verify/check if there are any scale issues present.

There are a number of factors that should be accounted for to report accurately on the uncertainty of the tests carried out.

- The limitations and accuracy of the unprocessed data.

- The limitations and accuracy of the results and conclusions drawn from the testing.

- Differing scale principles related to Reynolds, Froude, structural, power conversion chain, mooring representation.

- The standard deviation for the performance indicator as well as the characterization of resources.

- Differing facilities create individual uncertainties.

Experimental uncertainty is described generally in ISO/IEC Guide 98-3.

Experimental uncertainty is described specifically in the ITTC documentation. The ITTC also provide guidance and examples for dealing with uncertainties (ITTC 2008a; 2008b; 2014; 2017; 2008c).

Another source of useful information on uncertainty is the ISO/IEC 17025 general requirements for the competence of testing and calibration laboratories which is highly relevant for any testing facility carrying out testing of pre-prototype scale devices.

# 7   Reporting requirements

## 7.1   Overview

Reporting requirements for facility core parameters and test specific parameters include:

- Reporting of test conditions and goals
- Presentation of results
- Current parameters
- Wave parameters if applicable
- Control
- Presentation of performance indicators.

## 7.2   General

Reporting requirements are described below. All work performed should adhere to the requirements in this document, and any deviations shall be documented.

## 7.3   Test conditions and goals

### 7.3.1   General

The test planning considerations shall be documented in the reporting. This includes the design statement, testing goals, facility selection, physical model characteristics and a measurement procedure.

Special attention shall be given to identification of each relevant similitude that cannot be obtained, which should be included in the reporting along with a description of how this misrepresentation is expected to influence the scaling procedure to full scale. Where the facility characteristics do not entirely match the expected full-scale conditions, this should be noted in the reporting.

### 7.3.2   Facility selection report

The facility should be well defined in accordance with the details in Annex C. This

should include:

Physical characterization of the experimental test section.

- For Stage 1 and 2; a detailed drawing of the facility including:
  – Location of any flow conditioning
  – Dimensions of the test section
  – Location of any flow measurement instrumentation relative to the TEC.
- For Stage 3; a minimum of one hydrographical/navigational chart of the test site that is of suitable scale to demonstrate the following information:
  – TEC location (expressed in Latitude/Longitude or UTM in WGS84); for moored devices, typical TEC location at slack tide, flood tide, ebb tide and an illustration of the watch circle / TEC footprint experienced during the tests;
  – illustration of the TEC footprint (fixed device) or anchor location(s) (floating device);
  – TEC angular orientation relative to True North (where applicable for a fixed device);
  – electrical cable route and length (if applicable);
  – shoreline profile;
  – water depth and tidal range in terms of MLW and MHW, including the reference datum;
  – any nearby tidal gauges or environmental monitoring stations;

- any other notable features or infrastructure in proximity to the device;
- identification of the current measurement locations used during the tidal resource assessment (if made);
- reporting of the current profiler (e.g., ADCP) positions including a figure illustrating that the requirements of 9.4 are satisfied;
- reporting of the tidal ellipse and principal flow directions relative to the TEC as described in 9.3;
- reporting (with diagram) of the cross-sectional area of the testing location consumed by the TEC and foundation or mooring as described in 6.4;
- reporting of external constraints affecting or having the potential to affect typical device performance or operational periods as discussed in 6.5;
- reporting of any variation from the representative water density if used for the calculations as discussed in 6.1.3;
- reporting of the wave climate where applicable as described in 9.5.

### 7.3.3   Physical model report

The TEC under evaluation shall be described in full. As a minimum, the following parameters should be provided:

- type of energy capture technology employed and standard dimensions of the TEC. This should incorporate the use of a diagram, and include projected capture area, supporting foundation/platform/mooring system, and distance above the seabed for a bottom-mounted device or below the surface for a floating device;

- in the case of multiple turbine rotors the device equivalent diameter shall be reported;

- location of the energy extraction plane, relative to supporting structure (seabed or floating platform);

- description of the control system (device and software version);

- description of the power take-off system and power measurement techniques. A diagram detailing the power take-off system and location of the power measurement instruments should also be provided. Where applicable, dry and wet calibration calculations to account for losses should be provided in detail;

- all instrumentation used and its location on or relative to the TEC. A diagram should be used and detail given to the instruments in use, including any calibration.

### 7.3.4   Measurement procedure report

The objective of the measurement procedure is to collect data that meet a set of clearly defined criteria as dictated by the testing goals.

A description of the measurement procedure shall be provided. This includes:

- reporting of the time used for data acquisition, procedural steps, test conditions, sampling rate, and averaging time for each data set;

- a log book containing measurement details, observations and anomalies should be appended to the report.

### 7.4   Presentation of results

After calculating the required performance indicators, as stated for each testing goal, they should be presented in a relevant manner. The following clause describes a selection of performance indicators and statistics which ought to be included in data presentation. Table 3 describes the presentation requirements of continuously measured quantities.

**Table 3 – Presentation of continuously measured indicators**

| Performance indicator | Stage 1 and 2 | Stage 3 |
|---|---|---|
| Torque, power and thrust | Mean ± standard deviation<br>Max ± standard deviation<br>Min ± standard deviation | Same as Stage 1 and 2, but separated into flood and ebb phases of the tide. |
| Out-of-plane bending moment (eccentricity of thrust) | Recommended | Required |
| Blade bending moments | Stage 2 – Flapwise or flatwise | Flapwise and lead-lag or flatwise and edgewise |
| Rotational velocity and absolute position | Mean ± standard deviation<br>Abs. position recommended but not required | Mean ± standard deviation<br>Max ± standard deviation<br>Min ± standard deviation |
| Velocity, point measurement | Mean ± standard deviation | Mean ± standard deviation<br>Max ± standard deviation<br>Min ± standard deviation |
| Velocity inflow, shear profile | Mean ± standard deviation | Mean ± standard deviation<br>Max ± standard deviation<br>Min ± standard deviation |

IEC TS 62600-200 should be followed for power and velocity results presentation. For cross-flow turbines, measurements should be presented for an integer number of rotations, see Table 4.

**Table 4 – Presentation of discrete measured indicators**

| Performance indicator | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| Discrete events (for example local point loads, green water occurrence, slamming and impact events) | Count and identify wave conditions for which it happened | Peak magnitude and duration of each event.<br>Count and identify wave conditions for which it happened | Peak magnitude and duration of each event.<br>Count and identify wave conditions for which it happened. |

Discrete event are most likely to occur for floating platforms subject to wave conditions. See Clauses 11 and 12 for further detail.

## 8 Data acquisition

### 8.1 Signal conditioning

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

Special attention shall be paid to sensors that supply small output signals (voltages in the order of mV), as these are susceptible to contamination from electrical background noise (large motors, pumps, or variable frequency 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) If an instrumentation amplifier is needed it should be placed as close to the sensor as possible, providing signal amplification to a minimum of 1 V peak to peak or even better, output the amplified signal in the form of a current signal (4 mA to 20mA) which is less prone to electromagnetic contamination.

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

d) Some of the signal conditioning features described above may already be built into modern sensor equipment.

e) Route the motor control and mains cables away (circa 300 mm) from signal cables where possible. If signal and power cable shall cross each other, this should be done at 90° to minimize interference.

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

## 8.2  Sample rate

The main driver behind the high frequency content of tidal turbine model signal is the turbine blade frequency (turbine rotor rotational frequency multiplied by the number of turbine blades) and its harmonics.

Another source of high frequency content in turbine model signals comes from flow turbulence induced loads but at frequencies above 100 Hz, the turbulence energy content is very low and often lower than instrumentation noise floor so a sampling frequency of 200 Hz to 250 Hz shall be considered sufficient to capture the relevant flow turbulence induced loads. However, if the high frequency end of the flow turbulence induced loads is of particular interest for a specific experiment, the sampling frequency shall be increased in accordance with the instrumentation noise floor.

Special attention shall be paid when recording localized 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.

When setting the sampling frequency care shall be taken to avoid aliasing: the sampling frequency shall be at least twice the frequency of the highest frequency content expected in the signal (Nyquist criterion). More information on this can be found in Payne *et al.*, 2009.

## 8.3  Analogue to digital conversion and DAQ system

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

## 8.4  Frequency response

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

## 8.5  Data synchronization

All PTO 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 synchronized using a common trigger or time base. The time constant of the system and excitation source will determine the accuracy of the synchronization. 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. blade frequency or wave period). Lags between DAQ systems (e.g. optical sensors versus analogue sensors) may misalign samples. This should be checked during testing and evolve an

estimate of inaccuracy. This should also be considered when calculating derived values based on data from multiple DAQ systems, which should generally be avoided.

## 8.6    Data recording

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

## 8.7    Recording of supplementary test data

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

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

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

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

## 8.8    Calibration factors/Physical units

The relationship between the recorded signal unit (for example voltage) and the actual physical property (the calibration factors) shall be documented. Calibration shall be performed as a minimum, before and after testing to verify that sensors have not been damaged (plastically deformed) or drifted in signal output.

## 8.9    Instrument response functions

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

## 8.10    Health monitoring and verification of signals

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

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

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

## 8.11 Special data acquisition requirements for Stage 3 open ocean 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 organized and archived as recommended in IEC TS 62600-200.

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

- Redundancy of essential sensors;

- Alternative route monitoring options;

- Data collection or control strategies.

# 9 Testing environment characterization

## 9.1 General

It is critical to the interpretation of data that the testing environment conditions be carefully recorded. The testing environment for laboratory (Stage 1-2) and field testing at tidal energy site (Stage 3) will be characterized using different techniques. In the laboratory environment it is expected that the characteristics will be well defined, it is recognized that the marine environment is a complex hydrodynamic environment which shall be considered carefully in the experimental testing and development of the TEC.

## 9.2 Environmental measurements

For each development stage the environmental measurements outlined in Table 5 shall be performed with further information is provided in the cross-referenced subclause.

**Table 5 – Environmental measurements**

| Environmental measurement | Stage 1 | Stage 2 | Stage 3 | Further details in subclause |
|---|---|---|---|---|
| Inferred inflow velocity | Only required if direct inflow velocity measurements are not recorded from other sources. | Not required but can be presented. | NA | 9.3.2 |
| Inflow velocity (Point measurement) | Recommended but not required. | At least one source, ahead of the device, capable of resolving velocities into directional constituents. | At least one source, ahead of the device, capable of resolving velocities into directional constituents. | 9.3.3 |
| Inflow velocity (Shear profile) | Not required | Data required ahead of the device which covers the projected area of the device. Capable of capturing the shear profile. | At least one source required ahead of the device which covers the projected area of the device, this applies for both phases of the tide. Capable of capturing the shear profile. | 9.4 |
| Submersion (hub height) | Pre-defined through experimental design | Pre-defined through experimental design | At least one measurement source required with a fixed position relative to the turbine's axis of rotation. | NA |
| Waves | Not required | If applicable, monitor using a source with a known relative position to the device. Source shall be capable of resolving the waveform. | Required, monitor using a source with a known relative position to the device. Source shall be capable of resolving the waveform. | 9.5 |
| Turbulence | Not required | If applicable measure with same single source as inflow velocity measurement. | Deploy a measurement system ahead of the device. | 9.6 |
| Temperature | Can be inferred from previous measurements | Shall be measured and presented | Shall be measured and presented | 9.7 |
| Salinity/ conductivity | Can be inferred from previous measurements | Should be measured and presented, but as a minimum inferred from previous measurements | Should be measured and presented, but as a minimum inferred from previous measurements | 9.7 |

## 9.3 Inflow/ Onset velocity

### 9.3.1 General

For all experimental designs the inflow velocity along the axis of rotation shall be presented. Two approaches can be adopted: If there is no requirement for a synchronized inflow and turbine response measurement (Stage 1), the velocity can be measured at the location of the turbine rotor, but in its absence. Otherwise (Stage 2 and 3), the velocity shall be measured at a sufficient distance upstream (2-5 diameters) or perpendicular to the axis of rotation, in-line with the plane of rotation and outside the field of influence of the turbine rotor (1 diameter).

IEC TS 62600-200 has further details on these deployment parameters. In either case, the measurement location shall be reported relative to the turbine ensuring the measurements capture the undisturbed, 'free-stream' characteristics of the flow. Furthermore, the recording time period shall be reported and statistically significant, this will vary depending on the nature of the facility and experimental plan. In all cases the time period shall be reported and justifiable.

### 9.3.2 Inferred inflow velocity

Inferred inflow velocity maybe sources such as the towing velocity of a carriage along a towing tank, or a calibrated power setting on the pumps in a circulating flume. In all cases these shall discussed with the facility manager during experimental planning. Direct reporting of the uncertainty values or citation to the relevant analysis shall be made in the report. This form of velocity measurement is only acceptable at Stage 1 and may be used alongside other inflow measurements in Stage 2 testing. Inferred velocity measurements are not acceptable at Stage 3 testing.

### 9.3.3 Point measurement

For all Stage 2 and 3 testing a point measurement is recommended. It will provide an independent data source for validation of inferred inflow measurements and/or a bin within any profile measurements.

Furthermore, for Stage 2 and 3 testing a point measurement shall provide insight into the structure of the flow upstream, enabling the components of the flow to be resolved in 2 or 3 dimensions. For further information on point measurement instruments see Annex D.

## 9.4 Velocity shear profile

### 9.4.1 General

A velocity shear profile is the term used to describe the velocity gradient within a flow. Velocity Shear profiles occur in both the vertical and horizontal planes, and are often caused by boundary effects. The shear profile characterization is an important parameter to define and report when testing tidal turbines and shall be reported at all stages.

Stage 1 and 2 testing may experience shear profiles on the sides, top or bottom of the tank depending on the facility type and surface friction. Consult with the facility manager to determine if there is a known shear profile in the facility. In addition, the introduction of a turbine rotor in a facility may cause a shear profile due to blockage.

Stage 3 testing will experience a shear profile, it will likely be bathymetry and/or surface driven. In all cases, the boundary friction and device proximity to the boundary will play an important role in the significance of the shear profile and its effect on the testing.

Therefore, an instrument or array of instruments shall be used to resolve the shear profile.

### 9.4.2 Measuring a velocity shear profile

For all stages of testing the facility type will play an important role on the instrumentation that may be used. Table 6 shows the instruments capable of capturing a velocity shear profile in a particular facility at the relevant stage. Vertical and horizontal (lateral) shear occurring in water tunnels and open-channel flumes, and field test sites can alter the hydrokinetic power available. The section dimensions (width and height) are the relevant length scales relative to the corresponding device dimensions for assessing the degree of shear, and the need for measuring it.

Consistent with IEC TS 62600-300, vertical shear shall be measured if the device's projected height is greater than 25 % of the water depth, or the device is positioned such that its capture area overlaps with the bottom 25 % of the water column. Lateral shear shall be measured if the devices projected width is greater than the water depth.

**Table 6 – Instruments suitability for velocity profiling**

| Instrument name | Suitability for profiling |
|---|---|
| ADCP | • Ideal instrument for profiling applications, best suited for open-water and tidal test sites.<br>• Limitations exist in confined spaces due to wall reflections, such as small laboratory facilities.<br>• Open water pushing and tidal test sites may experience poor signal to noise ratio at times, post processing will require quality control. |
| ADV | • If a single instrument is used it will require a traversing carriage or shall be redeployed at distinct intervals. A multi-instrument array may avoid this need; however, shall avoid disturbing the inflow.<br>• For towing tank maintaining sufficient reflective particulates in the water can be an issue, consult with the facility manager prior to testing.<br>• Open water pushing and tidal test sites may experience poor signal to noise ratio at times, post processing will require quality control. |
| LDA | • If a single instrument is used it will require a traversing carriage or shall be redeployed at distinct intervals. A multi-instrument array may avoid this need; however, shall avoid disturbing the inflow.<br>• Rarely used as an array of instruments, but a possible option. |
| PIV | • Can be used for profiling in the laboratory environment (towing tanks and circulating flumes) typically over small fields of view.<br>• It is recommended to seek the advice of the facility manager if this approach is to be used. |
| Pitot-tube | • If a single instrument is used it will require a traversing carriage or shall be redeployed at distinct intervals. A multi-instrument array may avoid this need; however, shall avoid disturbing the inflow.<br>• Instrumentation has known limitations depending on variety, consult with instrument provider in relation to experimental test planning. |

NOTE Whilst the recommended instruments are most suited, the alternative instruments are commonly used. Typically, the choice is made by instrument availability and technical experience either of the facility operators or those conducting the experiments. Furthermore, it is recognized that for some facilities, such as a circulating flume, a point measurement device (such as an Acoustic or Laser Doppler velocimetry) may be used effectively due to the long periods of continuous testing achievable at such sites. Further information on these instruments may be found in Annex D.

If a shear profile is suspected in Stage 1 and 2, and for all testing at Stage 3 it is recommended that a sufficient number of bins/ discrete measurement locations across the projected area of the turbine is used to characterize the shear profile and its effect on performance (a minimum of 5 bins/ discrete readings across the projected area of the turbine is recommended). Depending on the turbine geometry and site bathymetry capturing a horizontal or vertical shear profile maybe justified. When this is the case and when calculating device power performance, the concept of shear velocity introduced in IEC TS 62600-200 shall be taken into account.

For all shear profile measurements, the recording time period shall be reported and statistically significant, this will vary depending on the nature of the facility and experimental plan. In all cases the time period shall be reported and justifiable.

### 9.4.3 Presenting velocity shear profile

The horizontal and vertical shear should be presented as cross-stream contour plots of the current speed profiles, line-plots of those profiles, or as tabulated data of those profiles in accordance with IEC TS 62600-200.

### 9.5 Wave climate

### 9.5.1 General

Waves cause a disturbance both at the surface of a body of water and penetrate into the body of water. In experimental testing the following wave types are typically used; regular waves, irregular long-crested sea states and irregular short-crested sea states (Draycott *et al.* 2017).

This subclause relates to the testing of a device in wave and currents. It does not include the sea keeping or stability of a platform in waves, considered in Clauses 11 and 12. Please see IEC TS 62600-101 for further information on these elements.

### 9.5.2   Measuring waves

Wave measurements are not required in Stage 1 testing, it is recommended at Stage 2 that experimental testing of wave-current interaction is performed, using regular and irregular waves on the device prior to Stage 3, if the device is anticipated to be deployed at sites that experience wave action.

The key wave measurement parameters are described in Table 7 (adapted from IEC TS 62600-103) provides the key parameters required when performing testing of these wave types.

**Table 7 – Environmental performance indicators**

| Environmental performance indicators | | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|---|
| Sea-states | Regular | Wave height $H$, ± standard deviation<br>Wave period $T$, ± standard deviation<br><br>Wave direction $\theta$, ± standard deviation<br><br>Water depth | | NA |
| | Irregular long-crested | Significant wave height, $Hs$<br>Zero up-crossing period, $Tz$<br>Energy period, $Te$<br>Peak period, $Tp$<br>Wave direction, $\theta$<br>Repeat time (if any)<br>Spectral shape | | NA |
| | Irregular short-crested | As irregular long crested waves, but including directional spreading | | NA |

At Stage 3 testing in irregular sea states the following shall be measured in accordance with IEC TS 62600-101.

It is noted that IEC TS 62600-103 and IEC TS 62600-101 have limited cross-application for wave-current testing of tidal energy converters. For example, due to the presence of current it is necessary to not only report the wave characteristics as formed by the wave paddle in the lab or inflow wave characteristics (stationary frame of reference) but to report the wave encounter characteristics. The wave encounter characteristics in a towing tank will consider the frequency change due to the carriage's velocity relative to the stationary reference frame.

### 9.6   Turbulence
### 9.6.1   General

The key performance metrics for turbulence and its significance to tidal energy converters are not currently known. This is the subject of ongoing research.

To date it is recognized that the following parameters affect performance and/ or loading of TEC devices and therefore it is recommended that they be reported for the incoming flow at Stages 2 and 3.

### 9.6.2   Turbulence intensity

Turbulence intensity is the ratio of the RMS of the turbulent velocity fluctuations to the mean flow speed. Mycek et al give details on the definition and significance of turbulence intensity (Mycek *et al.* 2014). The turbulence intensity is typically computed from the three velocity components but depending on the instrument used to measure velocity, it can also be calculated based on two or even one velocity components. In any case, the method used to calculate turbulence intensity shall be documented.

Due to the spatial variability and limitations in sample points it is currently recommended that the turbulence intensity be measured at the height of the rotational axis upstream of the TEC.

### 9.6.3   Integral length and time scales

Integral time and length scales are another means by which to characterize turbulence from the inflow. They describe the average duration and size of the turbulent features in the flow. Typically characterized in the longitudinal (axial), transverse and vertical orientations for a conventional axial-flow TEC device. These scales are significant for accurately representing turbine blade loading regimes and for turbine blade fatigue life analysis.

### 9.6.4   Other considerations

Accurate measurement and interpretation of the turbulence can be problematic due to the mathematical definition of the quantities where noise, instrument motion and spatially and temporally varying flow structures can contribute significantly to the magnitude of these statistics. The following laboratory or field test phenomena can impact the accuracy of the measurement of the turbulence. Ambient or instrument noise floors can increase the autocorrelation statistics and reduce the cross-correlation estimates. These noise sources will increase the spectral noise floor, masking some features of the flow spectra, and can be of a flat white noise spectral nature or frequency dependent. ADV noise is component dependent, the off-axis components exhibiting higher noise floors than the on-axis component. This increased noise in two of the three components of velocity will not only bias the normal statistics (increasing variance) but will also decrease the cross-correlations or Reynolds shear stress measurements.

### 9.7   Temperature, salinity, density and viscosity

Water temperature $T$, density $\rho$ and absolute viscosity $\mu$ are important fluid properties that shall be measured and reported for environmental characterization (Neary *et al.* 2011). For freshwater, density, viscosity and therefore Reynolds number are dependent directly on temperature as shown in tables in standard fluid mechanics or fluvial hydraulics texts (Chang 1988). Therefore, only the water temperature should be measured coincidental with the flow measurements in freshwater. In saline tidal environments, density and viscosity depend on both temperature and salinity, necessitating measurements of both temperature and conductivity (salinity being a function of conductivity and temperature). Standard protocols for measuring conductivity in tidal channels are detailed in Neary *et al.*, 2011. Detailed measurements of the water temperature and salinity, as well as the equation used to derive density, should be included to justify any variation from the representative value. If applicable the Thermodynamic Equation of Seawater (Intergovernmental Oceanographic Commission 2010) or should be used for seawater density calculations in this situation.

## 10   Turbine rotor performance characterization

### 10.1   Testing goals

The power performance testing shall produce an estimate of the hydrokinetic power converted by the TEC under different operating conditions, i.e., a power performance curve in either dimensional form (power in units of Watts [W] versus flow speed in metres per second [m/s]) or non-dimensional form (power coefficient versus tip speed ratio, i.e., non-dimensional power vs non-dimensional rate of rotation).

For Stages 1 and 2 the power conversion of the TEC under test should primarily be evaluated in suitable laboratory facilities, discussed in Annex C. In Stage 3 the power conversion of the TEC under test shall be evaluated in a real tidal flow.

When power performance curves are extrapolated to full scale and combined with data from a tidal energy resource assessment (IEC TS 62600-201), a riverine energy resource assessment (IEC TS 62600-300) or an ocean current resource assessment, the annual energy production (AEP) of a full-scale TEC can be estimated.

Scaled testing of the support structure, platform and moorings, should be considered if it affects tidal energy converter device performance and loading.

## 10.2 Performance indicators

### 10.2.1 General

The instantaneous kinetic power available in flowing water (in W) is equal to:

$$P_{available\ in\ flow} = 0,5\ \rho\ A\ U^3 \tag{6}$$

where

$\rho$ is the density of water, in $\mathrm{kg/m^3}$,

$A$ is the projected (flow-facing) area of the turbine, in $\mathrm{m^2}$, and

$U$ is the free-stream velocity approaching the turbine, in $\mathrm{m/s}$.

### 10.2.2 Power, torque and angular velocity

The power converted by the turbine rotor is:

$$P_{turbine} = T \times \omega \tag{7}$$

where

$T$ is rotor torque, and

$\omega$ is angular velocity.

To measure rotor performance, the shaft shall be loaded with a torque opposite the hydrodynamic torque such that energy is removed from the system. This energy shall then be dissipated. At the same time, turbine shaft angular velocity $\omega$ shall be measured. Torque should be measured as close to the turbine rotor as possible. If torque cannot be measured directly at the turbine rotor, losses between the rotor and the torque measurement location shall be evaluated.

### 10.2.3 Turbine rotor drag (thrust)

The turbine rotor drag or thrust, $F_D$, is the resulting force on the rotor in the principal flow direction due to the sum of all normal and shear stresses over the rotor. Instead of writing this force as integrals of stresses over an area, it is customarily expressed as being proportional to the projected area, $A$, and kinetic energy, $\frac{1}{2}\rho U^2$, with a drag coefficient, $c_D$, as a constant of proportionality. The turbine rotor drag (thrust) force is given as:

$$F_D = c_D, turbine\ rotor\ \frac{1}{2}A\rho U^2 \tag{8}$$

Cross-flow turbines also experience lateral forces. These depend on the cross-flow turbine design, and are typically smaller than the rotor drag (thrust force).

## 10.3 Non-dimensional performance indicators

### 10.3.1 General

It is advantageous to present results non-dimensionally, since this allows comparison between different turbine rotors.

### 10.3.2 Torque performance characterization

The non-dimensional torque coefficient is defined as:

$$c_Q = \frac{T}{0,5\ \rho\ A\ R\ U^2} \tag{9}$$

### 10.3.3 Power performance characterization

The fraction of the available kinetic power that is converted by the prime mover to shaft power prior to PTO losses is expressed as a non-dimensional ratio, the turbine rotor power coefficient:

$$c_{P,turbine\ rotor} \ = \ \frac{P_{turbine}}{P_{available\ in\ flow}} \ = \ \frac{T\ \omega}{0,5\ \rho A\ U^3} \tag{10}$$

The turbine power can then be expressed as:

$$P_{turbine} \ = \ c_P\ 0,5\ \rho\ A\ U^3 \tag{11}$$

### 10.3.4 Thrust performance characterization

Similarly, the ratio of the total thrust (rotor drag) force to the flux of kinetic energy per unit volume (also has units of force) is typically expressed as a ratio referred to as the thrust (drag) coefficient:

$$c_{D,turbine\ rotor} \ = \ \frac{F_D}{0,5\ \rho A\ U^2} \tag{12}$$

We note that power is proportional to flow velocity cubed, whereas drag is proportional to flow velocity squared.

### 10.3.5 Presentation of non-dimensional results

Power coefficient, thrust coefficient and torque coefficient can now be plotted against tip speed ratio. From the definition of tip speed ratio $\lambda$, , it can also be seen that:

$$c_Q = c_P/\lambda \tag{13}$$

Formulas (9) through (13) are for instantaneous quantities. These instantaneous quantities should be averaged over a suitable time interval, which will depend on facility, test article and test conditions.

## 11 Motions and loads under operational conditions

### 11.1 Testing goals

It is important to evaluate the motion and loads of the rotor/prime mover and any support structure, which may be fixed or floating. The purpose of this testing is to evaluate the loading on the support structure, mooring loads and platform motions (if applicable). In Stage 1 the platform motions and predominant cross-sectional loads are investigated through the use of RAO curves and bivariate scatter plots of load and motion versus input conditions. In Stage 2, local loads are investigated as well as more comprehensive measurements of the TEC cross-sectional loads, platform motions, and mooring characteristics where applicable. Lastly, in Stage 3 the loading (local, cross-sectional, and mooring) and motion characteristics of the TEC will be used to populate the bivariate scatter diagram.

### 11.2 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.

The parameters that shall be adopted for geometric and structural similitude for testing kinematics and dynamics are given in Table 8 and Table 9.

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 all cases, the mooring characteristics shall be verified experimentally.

Since the goal of this testing is motions and loads, achieving turbine rotor similitude is technically not required. However, since the kinematics and dynamics of a device are partially dictated by the operation of the rotor or PTO, a mechanism shall be implemented that achieves representative kinematics and dynamics.

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 8 and Table 9.

**Table 8 – Geometric similitude requirements (operational environments)**

| Geometric similitude | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| Turbine rotor | Thrust load to match the operational thrust to within 15 % at model scale; no rotational parts required | Thrust load to match the operational thrust to within 10 % at model scale; no rotational parts required | Thrust load to match the operational thrust to within 5 % at model scale; rotational parts required. |
| Platform | Major properties of profile scaled to match the produced environment to within 15 %; constrained DoF testing allowed | All dominant properties of the profile scaled to match full-scale design to within 10 % | All dominant properties of the profile scaled to match full-scale design to within 10 % |
| Mooring | Full layout (footprint) not essential | Full layout (footprint) not essential | All dominant properties and scaled to match scaling parameter |

**Table 9 – Structural similitude requirements (operational environments)**

| Structural similitude | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| Turbine rotor | Not essential | Not essential | Where possible, match the full-scale materials and construction techniques. |
| Platform | Not essential unless fundamental to power conversion | Not essential unless fundamental to power conversion | Where possible, match the full-scale materials and construction techniques. |
| Mooring | Not essential | Properties proportional to distance and velocity; as well as the scaled pre-tension scaled to represent full-scale design to within 20 % | Properties proportional to distance and velocity; as well as the scaled pre-tension scaled to represent full-scale design to within 10 % |

Typical Froude scale factors are in the order of 1:25 – 100 (Stage 1), 1:10 – 1:25 (Stage 2) and 1:1 – 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. Clause 6 provides addition scaling guidance.

## 11.3 Platform motions

Kinematic motions in each flow condition shall be measured. Table 10 identifies the kinematic measurement of the model and its subsystems in each stage required to successfully determine the performance indicators. Systems that are free to move such as floating systems or free-to-yaw devices should be monitored for position and acceleration. For example, the pitch of a floating device shall be monitored with respect to rotor thrust and mooring line tension. The purpose of the motion and loads testing is not to determine the power production, however, the kinematics and dynamics of the platform and structure are partially dictated by the turbine rotor or PTO performance (namely thrust). Often at smaller scales in Stages 1 and 2 assessing the platform response will benefit from porous plates that represent the rotors and exert a representative drag force (which should be measured directly).

**Table 10 – Kinematic signal measurements (operational environments)**

| Kinematic measurements | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| Platform | All independent and active DoFs for all bodies should be monitored to 5 % of the major length parameter of the model | All independent DoFs for all bodies monitored to 2 % of the major length parameter of the model | Global location of TEC in ocean |
| Mooring | Independent monitoring not essential. The TEC kinematics can be helpful in identifying the mooring kinematics | Recommended to monitor all attachment points of all legs (at optional buoyancy chamber, at anchor point) to 2 % of the major length parameter of the model | 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.

A full six DoF motion tracking system is recommended if available. Six DoF tracking systems require calibration, and this shall be undertaken with assistance from the tank/test 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. More information on motion tracking systems can be found in Clause D.9.

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.

## 11.4 Local loads, cross-sectional loads and mooring or global loads

Measurements capturing the forces and moments in each flow condition and wave train shall be made throughout the load path at the critical locations. Table 11 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 11 – Dynamic signal measurements (operational environments)**

| Dynamic measurements | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| TEC: Blade loads | Sensing not essential; | Blade loads should be measured (for example in flapwise and edgewise coordinates) | Blade loads shall be measured (for example in flapwise and edgewise coordinates) |
| TEC: Turbine rotor thrust and torque loads | Sensing not essential;. | Turbine rotor thrust should be measured | Turbine rotor thrust shall be measured |
| TEC: Platform 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 green water or slamming was seen in Stage 2. Monitoring recommended if impact event occurred in Stage 2. |
| TEC: Cross-sectional loads | Cross-sectional loads should be sensed in primary stress plane. | Cross-sectional loads shall be measured in primary stress plane and shall be measured in out-of-plane directions (alternatively the bending moments may be measured) | Cross-sectional loads shall be measured in 3 DoF. |
| Mooring | Floating: line in predominant wave direction at attachment point to TEC to result in a full-scale accuracy of 20 % of the expected peak load Fixed: connection point in one DoF in a full-scale accuracy of 20 % of expected peak load | Floating: all lines (including umbilical when relevant) at attachment point to TEC to result in a full-scale accuracy of 5 % of the expected peak load Fixed: connection point in six DoF with a full-scale accuracy of 5 % of the expected peak load (special attention to be paid to cross-coupling) | Floating: all legs to result in a full-scale accuracy of 3 % of the expected peak load Fixed: connection point in six DoF with a full-scale accuracy of 3 % of the expected peak load (special attention to be paid to cross-coupling) |
| PTO | Not required | Not required | All DoFs contributing to absorbed power |

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

The environment shall be monitored as specified in 9.2.

## 11.5  Test conditions

### 11.5.1  Stage 1 and 2

The minimum requirements for the laboratory (Stages 1 and 2) dynamic and kinematic tests should follow those outlined in Table 12. Current velocities shall be selected such that they adequately cover a representative range of site conditions. The wave tests may be omitted if the device not to be deployed at sites with wave action.

**Table 12 – Current parameters for kinematics
and dynamics testing (operational conditions)**

| Obtain dynamics and kinematics | Stage 1 | Stage 2 |
|---|---|---|
| Current | 1 flow velocity at in flood and ebb directions. | 3 flow velocities (of which one is in ebb and flow). |
| Varying current direction | Not required | Device response to changes in current direction should be investigated. |
| Regular waves in current | 3 periods for the design flow velocity per direction per configuration of the device for 50 waves duration each.<br><br>For selected configurations, the testing should be repeated with at least three additional wave amplitude. | 3 periods for 3 flow velocities per configurations of the model for 50 waves duration each.<br><br>For selected device configurations, the testing should be repeated with at least four other wave amplitudes. |
| Irregular long-crested sea states at a nominal direction | Generally outside the scope of Stage 1 testing | 6 operational sea states (for each tested spectral shape) of 250 waves duration each. |
| Irregular short-crested sea states | Generally outside the scope of Stage 1 testing | Generally outside the scope of Stage 2 testing |

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

In the case of a freely yawing device, the various current directions may be disregarded with respect to the device, however, the response to changes in current direction should be investigated. In experimental studies, regular wave conditions have shown to increase thrust loads by up to 65 % compared to current-only loads at rated power (Draycott, Payne, et al. 2019). Irregular waves have shown to increase this to above 90 % (Draycott, Steynor, et al. 2019).

### 11.5.2 Stage 3

For open ocean trials, the test schedule shall be constructed such that changes to the device configuration, especially the turbine rotor torque or speed settings, can be compared across a statistically significant number of tidal cycles. The purpose is to quantify the device behavior for each device setup.

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

### 11.5.3 Fatigue measures

Measurement of the loads through the device should enable designs to carry out fatigue analysis. While we recognize this is important, it is not covered in more detail at this time. It may be covered in a future revision of this document.

## 12 Motions and loads under survival conditions

### 12.1 Testing goals

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

The magnitude of the worst case 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 TEC and support structure given a device's response to various incoming environments.

If specific survival strategies, i.e. strategies such as locking the turbine rotor to alter the device response to environmental forcing shall be tested.

Floating or otherwise free to move TECs may require dedicated models designed specifically for survival conditions due to the scale of the environments. An additional element that shall be considered for these models is the electrical umbilical that transports power from the TEC.

There are no specific requirements on the generation of the survival environment in Stage 1 to determine the kinematics and dynamics in survival environments; however, results from this stage shall be used to qualitatively select appropriate survival strategies.

In Stage 2, local loads and TEC cross-sectional loads along with TEC motions and mooring loads are all used to characterize the device's peak responses.

In Stage 3, the naturally occurring environment will not only provide data to further characterize the device response similarly to Stage 2, but additionally will allow for characterization of the construction and equipment selected.

## 12.2   Testing similitude

The parameters that shall be adopted for geometric and structural similitude for testing kinematics and dynamics in survival environments are given in Table 13 and Table 14. Stage 2 contains the majority of similitude requirements that are unique from those presented in Table 9 since at this stage a full testing program to determine statistically significant PDFs shall occur.

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

**Table 13 – Geometric similitude requirements (survival environments)**

| Geometric similitude | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| Turbine rotor | Thrust load to match the estimated operational thrust to within 15 % at model scale; no rotational parts required | Thrust load to match the estimated operational thrust to within 10 % at model scale; no rotational parts required | Thrust load to match the estimated operational thrust to within 5 % at model scale; no rotational parts required |
| Platform | Major properties of profile scaled to match the produced environment to within 15 %; constrained DoF testing allowed | All dominant properties of the profile scaled to match full-scale design to within 10 % | All dominant properties of the profile scaled to match full-scale design to within 5 % |
| Mooring | Full layout (footprint) not essential | Full layout (footprint) not essential | All dominant properties and scaled to match scaling parameter |

**Table 14 – Structural similitude requirements (survival environments)**

| Structural similitude | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| Turbine rotor | Not essential | Not essential | Where possible, match the full-scale materials and construction techniques, even if this will result in skewed scaling for the structural response |
| Platform | Not essential unless fundamental to survivability | Not essential unless fundamental to survivability | Where possible, match the full-scale materials and construction techniques, even if this will result in skewed scaling for the structural response |
| Mooring | Not essential | Properties proportional to distance and velocity; as well as the scaled pre-tension scaled to match full-scale design to within 10 % | Properties proportional to distance and velocity; as well as the scaled pre-tension scaled to match full-scale design to within 5 % |
| Electrical umbilical | Not essential | Properties proportional to distance and velocity; as well as the scaled pre-tension scaled to match full-scale design to within 20 % | Properties proportional to distance and velocity; as well as the scaled pre-tension scaled to match full-scale design to within 10 % |

## 12.3 Signal measurements

For requirements regarding signal measurement please refer to Clause 8 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 for floating platforms, especially at Stage 2.

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

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

## 12.4 Environmental Input parameters

### 12.4.1 General

It is also recommended that combined waves and current form part of the survival test program. In the absence of site specific data, the waves and current can be run co-linear for head and quarter seas.

### 12.4.2 Stage 1 and 2

Both ebb and flow directions for operational current conditions shall be investigated for survival seas. Floating structures should investigate beam on waves if applicable.

An extreme sea state where the TEC is in survival mode (as defined in IEC TS 62600-1). Normally characterized by a wave height and wave period with a large return period (e.g. 50 years).

If a specific deployment site is identified those conditions should be used.

### 12.4.3 Stage 3

A survival strategy shall be developed. If feasible, during Stage 3 open ocean trials the TEC should be exposed to extreme conditions to verify the survival strategy.

### 12.5 Performance indicators

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

The characterization of the continuous response shall be based on the kinematic (TEC, location of mooring line seabed contact, if relevant any other mooring bodies kinematics, and the umbilical kinematics) and dynamic (TEC local loads, TEC cross-sectional loads, mooring loads, and umbilical loads) measurements as well as the environmental measurements. For each of these performance indicators, the reporting outlined in Clause 7 shall be adopted.

For floating devices the characterization of the discrete response shall be based on counting the number of slamming events, green water events, snap events in the mooring, and snap events in the umbilical. The device should also be able to maintain position and not subject to porpoising.

## 13 Testing of arrays

TECs are most likely to be deployed in array configurations, while we recognize this is important with respect to performance and extreme conditions it is not covered in more detail at this time. It may be covered in a future revision of this document.

When TECs are deployed in array configurations, the onset flow may be accelerated or decelerated and redirected from the nominal flow direction and speed (Sutherland *et al.* 2018). This can lead to a change in device performance and loading depending on the TEC location within the array.

This can lead to a change in device performance and loading depending on the TEC location within the array and the spacing of turbines in the array (Noble *et al.* 2020). The optimization of array configurations may be better evaluated in numerical modeling studies, however, a model validation case should be carried out experimentally.

# Annex A
(informative)

## Stage gates

### A.1    General

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 program, but additional evaluations, relevant to the goal-oriented trials, are recommended. It is also recommended that a 3rd party technical review is conducted on the evolving design to ensure the device can be engineered and will achieve certification status when at the prototype scale.

### A.2    Design statements

As stated in Clause 6, at the beginning of the test program, a design statement should be produced listing the expected behavior 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 program. 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 tidal current 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 tidal energy conversion (TEC) 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 TEC 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 predictions in two ways. Firstly, by strategically applying more criteria into the Stage Gate evaluation and secondly by progressively increasing the physical size of the device model. As described in Clause A.4, 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 analyzed performance matrix results. Among others, construction methods, PTO manufacture, routine servicing and maintenance and deployment can be considered briefly. The primary focus at Stage Gate 1 the testing and evaluation of the behavior and power conversion ability of the device under representative tidal conditions.

Stage 2 [TRL4]; During the medium-size device program (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 5.3 and these are used as the basis to specify the Stage Gate criteria in 5.3.2.

Stage 3 [TRL5 and 6]; The large-size model is a fully operational unit deployed at sea and testing in naturally occurring tidal conditions.

## A.4    Uncertainty factors

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

- Measurement inaccuracy during the testing;
- Limited test programs;
- 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 program 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 program; 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 Reynolds 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 Reynolds 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 X, such that the results measured in a 1:50 model multiply by a factor of Y. Such multipliers do not instill 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 5.2.2, 5.3.2 and 5.4.2.

## A.5    Third party review

It is not uncommon that device concepts, tested as idealized small models, particularly in Stage 1, can initially prove successful as energy converters but may 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 open ocean 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 investigated 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)

## Device type

### B.1    General

Tidal Energy Converters (TECs) extract energy from moving water and convert it to electrical energy or other useable forms of energy. TECs can be classified by: how the momentum of water is converted to mechanical motion, e.g., rotational systems (turbines) vs. oscillatory systems; bottom-mounted vs moored in water column vs deployed from a floating platform; single-rotor vs multi-rotor; etc. In addition, some device types are unique and cannot easily be classified by these categories, for example underwater tidal kites.

The classification of rotational (turbine) TECs is primarily based on the orientation of the rotational axis with regards to the tidal flow direction: Axial-flow turbines are similar to conventional horizontal axis wind turbines, with their axis of rotation parallel to the tidal flow direction. Axial-flow turbines are sometimes referred to as "horizontal axis turbines". Cross-flow turbines, on the other hand, have their axis of rotation oriented perpendicular to the tidal flow direction, typically either in a vertical or horizontal direction. Cross-flow turbines are sometimes referred to as "vertical axis turbines".

Due to the existing diversity in TEC devices a comprehensive guide to experimental testing and development for all types through the Stage Gates was not considered viable. Therefore, this document was written primarily for axial-flow and cross-flow turbines, either bottom-mounted, moored or floating. It is recognized that many of the procedures described in this document can be applied to other TEC device types as well. Therefore, this annex briefly introduces the characteristics of various TEC device types and discusses the limitations of the testing information presented in this document.

### B.2    Axial flow turbines

Axial-flow turbines typically utilize multi-bladed rotor concepts similar in design to modern horizontal axis wind turbines. Axial-flow turbines consist of one or more turbine rotors connected to a power-take-off (PTO). The turbine rotor/PTO assembly is mounted to a tower in either an upstream (turbine rotor upstream of tower) or downstream (turbine rotor downstream of tower) configuration. These devices can be mounted to the seabed floor, fixed at the surface to a floating barge/platform, or can be moored submerged, mid-water column. These variables in mounting (upstream vs. downstream configuration, and bottom-mounted vs. mooring) can be important factors to consider for model testing; as these factors can impact device performance, device loading and blockage corrections. Axial-flow turbines typically need to be able to rotate around their towers (yaw) to face the oncoming flow, unless the turbine rotor design uses bi-directional turbine blades and the deployment location has negligible directional asymmetry for the reversing tidal flow. Some axial-flow variations which are currently under development include counter-rotating rotors on a TEC device. These are designed to minimize global axial moments on the device, facilitating a floating tethered mooring configuration.   The methodologies for testing such a device will be similar, however, some differences are likely. For such a design, careful consideration of the intra-cycle dynamics between the two rotors will be necessary.

### B.3    Cross-flow turbines

Cross-flow turbines are characterized by an axis of rotation that is perpendicular ("cross") to the tidal flow direction. Lift-driven cross-flow turbines originated with the vertical axis Darrieus wind turbine concept. Cross-flow TEC devices often are of the straight-bladed, H-Darrieus type or of the H-Darrieus type with helical blades, which are referred to as Gorlov turbines. The primarily drag-driven Savonious turbine concept can also be utilized, but is less common. Both vertical axis and horizontal axis cross-flow TECs exist. Due to their operating principle, cross-flow TECs are inherently unsteady devices and their device dynamics should be carefully considered. Similar to axial-flow turbine TECs, cross-flow turbine TECs incorporate a PTO assembly, and can be bottom-mounted, moored or deployed from a floating platform. Cross-

flow turbines will rotate in the same direction regardless of flow direction (as long as the flow is perpendicular to the turbine axis) and do not need to yaw into the oncoming flow. Cross-flow turbines have two principal dimensions, diameter and height, and an aspect ratio can be selected to best occupy the available tidal channel cross-section.

## B.4 Hydrofoil devices

A hydrofoil device TEC utilizes a hydrofoil which can change angle of attack and is attached to an oscillating arm. The hydrofoil induces hydrodynamic lift and drag forces due to a pressure difference on the foil section caused by given a positive or negative angle of attack relative to the tidal stream in-flow over the foil section. These forces induce a resultant tangential force to the arm, and as the angle of attack of the hydrofoil is changed the arm moves in alternating directions. This motion then drives a linear generator or pressurizes fluid in a hydraulic system. Many of the testing methodology principles outlined in this document also apply to hydrofoil devices, although in scale model testing practice these devices are quite different from rotating devices.

## B.5 Other

### B.5.1 Ducted devices

A well-designed duct can accelerate the flow towards the turbine rotor to increase the power output of the turbine. A flow-accelerating duct can be used with axial-flow turbine TECs, cross-flow turbine TECs and other TEC types. Ducted devices have increased drag compared to non-ducted devices of the same turbine rotor dimensions. The testing methodology outlined in this document also applies to ducted devices. To enable a meaningful comparison to non-ducted devices, the turbine rotor power efficiency should also be reported with the maximum duct cross-sectional area as the reference area.

### B.5.2 Oscillating devices

Oscillating devices often rely on cyclic vortex shedding to excite a lifting surface or cylinder into a controlled, cyclic motion, characterized by the Strouhal number. The motion of the moving structure is then coupled to a mechanical or pneumatic/hydraulic drive system connected to the PTO. This converts oscillatory motion into linear or rotating motion which can be used to drive a generator, while a pneumatic/hydraulic system can be used to pump a fluid through a turbine driven generator. The methodology for assessing the performance of an oscillating device is outside of the scope of this document.

### B.5.3 Underwater kites

Underwater kites represent a different class of TEC devices. The tidal energy conversion system typically consists of an axial-flow turbine, nacelle and PTO. However, inflow velocity and overall turbine dynamics are more complicated, since the axial-flow turbine experiences the relative motion of the kite moving through the water. The kite's path features large sweeps which can create shear profiles of their own across the projected area of the turbine. Furthermore, there is coupling between the extracted power from the turbine and the speed of the kite, with additional dynamic responses from the kite wing, rudder, struts, and tether. In the turbine rotor plane-of-reference the turbine can be considered an axial-flow turbine, however, due to the higher velocities and smaller area the turbine blade design will require particular attention. Testing this type of TEC at a small scale may be difficult due to the high velocities required. The motion and loads on underwater kite TECs under operational and survival conditions will be very different compared to standard axial-flow TECs and are beyond the scope of this document.