Tidal-current Energy Device
Development and Evaluation Protocol
Tidal-current Energy Device Development and Evaluation Protocol

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Contractor
University of Southampton

The work described in this report was carried out under contract as part of DECC Marine Renewables Deployment Fund, which is managed by AEA. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of DECC or AEA.

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This document describes a Protocol to manage the development of tidal-current energy devices, from concept formulation to full-scale demonstration. The Protocol, commissioned by The Department for Business, Enterprise and Regulatory Reform (BERR), in September 2007, was developed by the Sustainable Energy Research Group (SERG) at the School of Civil Engineering and the Environment in the University of Southampton.

The overall aim of this Protocol is to assist in cost-effective management of research and development of tidal-current power technology, while allowing device developers to benefit from the confidence generated by using commonly accepted measures of performance.

A draft Protocol for consultation was disseminated in June 2008, followed by a workshop held at BERR in July 2008. The Protocol was then comprehensively revised into the version presented here, taking into account the comments received from industry and academia.

Details of the thinking behind the Protocol, along with supporting data, are included in two separate companion reports which are part of the SERG scientific report series (www.energy.soton.ac.uk). The first report developed the background for establishing the Protocol and is entitled, “Formulation of the Tidal-current Energy Device Development and Evaluation Protocol” (Bahaj et al., 2008a). The second companion report contains a set of adaptable templates for reporting compliance with the Protocol, along with supplementary information and is entitled, “Model templates for reporting and supplementary information for the Tidal-current Energy Device Development and Evaluation Protocol” (Bahaj et al., 2008b).

The Protocol is part of BERR’s contribution to the International Energy Agency Implementing Agreement on Ocean Energy Systems (IEA-OES) and will form the deliverable of the UK-led Task 2.2 of the IEA-OES Annex II Extension.
A full account of the Consultation Workshop is included in Appendix C. Attendees are listed below:

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<th>Organization</th>
</tr>
</thead>
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<tr>
<td>Mr Alan Morgan</td>
<td>BERR</td>
</tr>
<tr>
<td>Mr Trevor Ragatt</td>
<td>BERR</td>
</tr>
<tr>
<td>Mr Steve Wyatt</td>
<td>Carbon Trust</td>
</tr>
<tr>
<td>Mr Bill Edgar</td>
<td>EMEC</td>
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<tr>
<td>Dr Peter Fraenkel</td>
<td>Marine Current Turbines</td>
</tr>
<tr>
<td>Mr Roger Taylor</td>
<td>Strachan &amp; Henshaw</td>
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<tr>
<td>Dr Fred Gardner</td>
<td>Teamwork Technology &amp; Tocardo</td>
</tr>
<tr>
<td>Mr Jeremy Thake</td>
<td>Tidal Generation Ltd</td>
</tr>
<tr>
<td>Mr Brian Holmes</td>
<td>University College, Cork</td>
</tr>
<tr>
<td>Professor Ian Bryden</td>
<td>University of Edinburgh</td>
</tr>
</tbody>
</table>

Written comments received have also been included in Appendix B.

Prof AbuBakr S Bahaj, Luke Blunden and Dr Arif Anwar

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Sustainable Energy Research Group
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Southampton
SO17 1BJ
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August 2008
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## Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>Defined here as the percentage of ‘potential operating time’ (i.e. time where the flow speed is above the cut-in speed for the device) in a given period, when the device is actually operating.</td>
</tr>
<tr>
<td>BERR</td>
<td>UK Government Department of Business, Enterprise and Regulatory Reform (formerly called the Department of Trade and Industry (DTI))</td>
</tr>
<tr>
<td>BEM</td>
<td>Blade-element momentum. An analytical methodology for designing propeller-type rotors, simpler and less computationally intensive than CFD.</td>
</tr>
<tr>
<td>Breadboard</td>
<td>Electronics term used to describe rapid prototyping of electronic systems using discrete components, fixed together in a non-permanent way.</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics.</td>
</tr>
<tr>
<td>Component</td>
<td>Part of a subsystem; may vary considerably between different devices</td>
</tr>
<tr>
<td>Commercial demonstrator</td>
<td>A full-scale model of a tidal-current power device substantially complete and including all technologies; last stage before commercial production</td>
</tr>
<tr>
<td>DNV</td>
<td>Det Norske Veritas, an RCS</td>
</tr>
<tr>
<td>Equivalent diameter</td>
<td>Diameter of a circle with the same area as the flow capture area of the device. Where the device has two or more discrete capture areas per support structure or mooring, the area for the purposes of equivalent diameter is the sum of the discrete areas.</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>Flow capture area</td>
<td>For un-ducted devices, the vertical area swept by the hydrofoils. For ducted devices, the largest cross-sectional area of the duct.</td>
</tr>
<tr>
<td>GL</td>
<td>Germanischer Lloyd, an RCS</td>
</tr>
<tr>
<td>Hydrofoil</td>
<td>A surface designed to give rise to lift when moving through water. An example would be a propeller-type blade on an axial flow tidal-current turbine</td>
</tr>
<tr>
<td>IEA-OES</td>
<td>International Energy Agency Implementing Agreement on Ocean Energy Systems</td>
</tr>
<tr>
<td>Levelized cost of energy</td>
<td>Result of Net Present Value calculation giving the present cost of energy that will result in break-even over a lifetime of a project with a particular discount rate applied.</td>
</tr>
<tr>
<td>Novel</td>
<td>Term used to describe subsystem components or procedures, which represent large departures from the body of existing knowledge within the offshore, marine and wind industries as encapsulated in established Standards and guidelines.</td>
</tr>
<tr>
<td>Off-specification</td>
<td>Refers to a commercial product that will be used outside the operating envelope specified by the manufacturer</td>
</tr>
<tr>
<td>Prototype</td>
<td>A full-scale model of a tidal-current power device subject to further development</td>
</tr>
<tr>
<td>Rated power</td>
<td>Where there are two or more discrete generators on a support structure or mooring, the rated power is the sum of the individual rated powers.</td>
</tr>
<tr>
<td>RCS</td>
<td>Recognized Classification Society, e.g. DNV or GL.</td>
</tr>
<tr>
<td><strong>Sea-trial</strong></td>
<td>A series of tests, in this case on a tidal-current energy device, to ensure all subsystems perform adequately at sea</td>
</tr>
<tr>
<td><strong>Stage-gate</strong></td>
<td>Generic technology development methodology described in Cooper (1990)</td>
</tr>
<tr>
<td><strong>Subsystem</strong></td>
<td>Generic subsystem of a device</td>
</tr>
<tr>
<td><strong>Tidal-current</strong></td>
<td>Continental shelf current driven by periodic tidal forcing. Also known as a tidal stream.</td>
</tr>
<tr>
<td><strong>TRA</strong></td>
<td>Technology Readiness Assessment. A systematic measurement system developed by NASA in order to support assessments of the maturity of a particular technology</td>
</tr>
<tr>
<td><strong>TRL</strong></td>
<td>Technology Readiness Level. A series of nine levels of development from initial idea to final system, used in Technology Readiness Assessment</td>
</tr>
<tr>
<td><strong>TSR</strong></td>
<td>Tip Speed Ratio. Equivalent to ( \lambda ) for an axial flow device</td>
</tr>
<tr>
<td><strong>UoS</strong></td>
<td>University of Southampton, UK represented by the Sustainable Energy Research Group (SERG) in the School of Civil Engineering and the Environment</td>
</tr>
</tbody>
</table>
# NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Variable</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$c$</td>
<td>Chord of hydrofoil section</td>
<td>m</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Power coefficient (shaft power)</td>
<td></td>
</tr>
<tr>
<td>$C_{PE}$</td>
<td>Power coefficient (electrical power)</td>
<td></td>
</tr>
<tr>
<td>$C_T$</td>
<td>Thrust coefficient</td>
<td></td>
</tr>
<tr>
<td>$D$</td>
<td>Vertical extent of hydrofoil (e.g. rotor diameter)</td>
<td>m</td>
</tr>
<tr>
<td>$Fr$</td>
<td>Froude number</td>
<td></td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity</td>
<td>$m , s^{-2}$</td>
</tr>
<tr>
<td>$h$</td>
<td>Depth of water</td>
<td>m</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
<td>$N , m^{-2}$</td>
</tr>
<tr>
<td>$P$</td>
<td>Power</td>
<td>$W$</td>
</tr>
<tr>
<td>$Q$</td>
<td>Torque</td>
<td>$N , m$</td>
</tr>
<tr>
<td>$r$</td>
<td>Ratio</td>
<td></td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>Thrust</td>
<td>$N$</td>
</tr>
<tr>
<td>$U$</td>
<td>Flow speed</td>
<td>$m , s^{-1}$</td>
</tr>
<tr>
<td>$V$</td>
<td>Apparent flow speed at hydrofoil</td>
<td>$m , s^{-1}$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Ratio of hydrofoil speed to flow speed</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of seawater</td>
<td>$kg , m^{-3}$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Cavitation number</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity of seawater</td>
<td>$m^2 , s^{-1}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular shaft speed</td>
<td>$rad , s^{-1}$</td>
</tr>
</tbody>
</table>

Subscripts

- $0$ Undisturbed
- $a$ Atmospheric
- $b$ Blockage
- $f$ Full-scale
- $H$ Hydrofoils
- $I$ Immersion
- $m$ Model
- $max$ Maximum
- $t$ Tunnel
- $v$ Vapour
INTRODUCTION

Summary

This document describes a Protocol to manage the development of tidal-current energy devices, also referred to as tidal stream devices.

The Protocol recommends a ‘stage-gate’ approach to development with a total of five stages and gates. A stage represents the development activities and the gate is the point of evaluation of those activities, where a decision is taken to proceed to the next level or perhaps to iterate within the same level until certain criteria specified in the gate are fulfilled. Each stage is subdivided into technical development and evaluation, followed by economic evaluation. The economic evaluation is refined at each stage, to produce a range of estimates of the final cost of energy for a particular size array of devices.

The Development Stages 1 to 3 entail mandatory testing and analytical requirements in conjunction with developer-defined Research and Development. Stages 4 to 5 are concerned with full-scale testing in the sea.

Details of the thinking behind the Protocol are included in a separate companion report entitled, “Formulation of the Tidal-current Energy Device Development and Evaluation Protocol” (Bahaj et al., 2008a). A second separate report contains a set of adaptable templates for reporting compliance with the Protocol, and is entitled, “Model templates for reporting and supplementary information for the Tidal-current Energy Device Development and Evaluation Protocol” (Bahaj et al., 2008b). Both reports form part of the SERG scientific report series (www.energy.soton.ac.uk).
Motivation for the Protocol

The Department for Business, Enterprise and Regulatory Reform (BERR), acting in its capacity as UK representative to the International Energy Agency Implementing Agreement on Ocean Energy Systems (IEA-OES), has commissioned The University of Southampton (UoS) to prepare a Protocol for the development and evaluation of tidal-current energy devices from initial conception to full-scale demonstration. The final Protocol will form the deliverable of the UK-led Task 2.2 of the IEA-OES Annex II Extension.

Objectives and Scope

The overall aim of this Protocol is to assist in cost-effective management of research and development of tidal-current power technology, while allowing device developers to benefit from the confidence generated by using commonly accepted measures of performance. This aim will be fulfilled through the following objectives:

1. Separate the development process into a number of clearly defined stages, with increasing certainty in the techno-economic viability of the devices at each stage.
2. Define appropriate variables representing the performance of the devices at each stage, based on a review of the published literature on device development and a consultation with industry stakeholders.
3. Set minimum threshold values of the performance variables that the device would need to exceed to progress to the next stage of development.
4. Set minimum standards for model similitude and collection, reduction and reporting of experimental data.
This Protocol applies to zero-static head flow machines designed to generate power from tidal-currents. The focus here is upon the development of new technology for tidal-current energy conversion, and the Protocol does not address important processes such as:

- Obtaining consents
- Environmental assessment
- Hydrographic and geotechnical investigations
- Connection to an electrical distribution network or the National Grid
- Assessing possible flow interactions within an array of turbines
APPROACH

Technology Readiness Assessment

The Protocol broadly follows the approach of Technology Readiness Assessment (TRA), developed by NASA to manage the development of technology as part of the space programme. It has since been adopted by the US Department of Defence, the US Air Force and the UK Ministry of Defence. Reference (Bahaj, Blunden and Anwar, 2008a) describes TRA and gives justification of its application in this case. The broad approach is to break down a system into subsystems and components, each to be developed in a number of stages or Technology Readiness Levels (TRLs), leading on to the integrated system development in the latter stages.

Table 1 shows how the NASA TRLs have been adapted in the Protocol to Stages of development for tidal-current power systems. The left hand side is taken from the TRL White Paper (Mankins, 1995). The right hand side outlines five stages of development addressed in this Protocol: Stage 1 consists of concept formulation, defining research and development (R&D) requirements and establishing basic theoretical models of performance. Stage 2 covers computational analysis, intermediate-scale model testing and laboratory testing of components, whereas Stage 3 involves large-scale testing of subsystems. Stage 4 covers full-scale prototype testing in the sea, followed by Stage 5, extended testing of the commercial demonstrator device in the sea.

The ultimate goal at each stage of development is to assess whether the production tidal-current energy device is technically and economically viable, with increasing certainty at each stage. The uncertainty in the estimate of the final cost of energy is large in the initial stages, but will reduce as the design parameters such as thrust, rated power, and capacity factor are known with greater accuracy. Therefore, confidence in the design parameters should be increased incrementally through tests of
increasing realism carried out as part of the developmental stages.

Table 1. NASA TRL terminology compared to Stages used in the Protocol

<table>
<thead>
<tr>
<th>TRL</th>
<th>NASA description</th>
<th>Tidal-current Protocol</th>
<th>Protocol Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and reported</td>
<td>Not applicable – this refers to fundamental scientific research.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Technology concept and/or application formulated</td>
<td>Tidal-current energy conversion concept formulated (Scope of Protocol begins here)</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Analytical and experimental critical function and/or characteristic proof-of concept</td>
<td>▪ Subsystem testing at intermediate scale</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>▪ Computational Fluid Dynamics</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>▪ Finite Element Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>▪ Dynamic analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Component and/or breadboard validation in laboratory environment</td>
<td>Subsystem testing at large scale</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Component and/or breadboard validation in relevant environment</td>
<td>Full-scale prototype tested at sea</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>System/subsystem model or prototype demonstration in a relevant environment (ground or space)</td>
<td>Commercial demonstrator tested at sea for an extended period. (Scope of Protocol ends here)</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>System prototype demonstration in a space environment</td>
<td>Production</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Actual system completed and “flight qualified” through test and demonstration (ground or space)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Actual system “flight proven” through successful mission operations</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The focus of this Protocol is on the development of tidal stream energy devices as a whole. However, in some cases, it may be that only one subsystem or a component of a subsystem is being developed. The Protocol can still be used to assess whether a production tidal-current energy device incorporating that subsystem or component is technically and economically viable. However, ‘default’ estimates of costs relating to the other subsystems would need to be used to complete the techno-economic assessment. Appropriate cost estimates would need to be provided by the subsystem developer, either through primary contacts and/or research by the developer, or by the use of published secondary data. The sources of the estimates would need to be properly referenced in all cases.
References to possible published sources of data that could be used under such circumstances are included in the section Economic Analysis Methodologies on page 27.

The Protocol is intended to be a dynamic document, which may be refined and adapted to suit specific cases and changing technology development needs. In the future, some aspects of the Protocol would be expected to reference appropriate standards, when tidal-current energy conversion technology reaches maturity.

The approach taken in this Protocol is not to be unnecessarily prescriptive of testing requirements, but rather to insist that the results follow closely theoretical and computational predictions of performance, at each stage of development. This in turn helps to reduce the uncertainty in the cost of energy estimates, which ultimately determine the likelihood of success.
System, Subsystems and Components

The term ‘system’ in this Protocol refers to the entire functioning device, composed of generic subsystems as sketched in Figure 1 (subsystems are capitalized). Most tidal stream energy converting devices for electrical power generation can be broken down into subsystems comprising hydrodynamics, power take-off, control and reaction. There may be considerable overlap between the subsystems, however. The lower-case items in Figure 1 are components, which may or may not be present in every device and may vary considerably between devices. A ‘scale model’ of the system or a subsystem, is a physical model produced to test specific aspects of the design. A ‘prototype’ is a functioning, full-scale system, but subject to significant further design changes, whereas the ‘commercial demonstrator’ is a device approaching readiness for production, with only minor changes envisaged.

Figure 1. Generic subsystems (capitalized) and components (lower case) in a tidal stream energy conversion device
Hydrodynamic Subsystem
This subsystem may be composed of blades of the conventional axial flow propeller type, orthogonal flow Darrieus type, oscillating hydrofoils or other arrangements. The purpose of these components is in most cases is to generate lift, causing the hydrofoils to travel faster than the local flow speed and consequently enabling power to be developed efficiently. Flow-augmentation components such as a diffuser may also form part of the hydrodynamic subsystem.

Reaction Subsystem
The purpose of this subsystem is to transfer the thrust on the device to the ground, maintaining the position and stability of the device. This may be achieved via a structure, a moored floating platform, direct moorings or a tension leg arrangement. The device may be founded using various piled, anchored or gravity solutions, possibly augmented by hydrodynamic down-force.

Control Subsystem
The purpose of the control system is to ensure that the thrust, torque, rotational speed and power of the electro-mechanical system remain within the design limits and as close as possible to the optimal operating point or points. It must also ensure that electrical power is of sufficient quality for delivery to the electricity distribution network. The control system may be required to orientate all or part of the system to face head on to the flow direction. Finally, the control system must allow the remote operator to start up and shut down the device safely in an emergency or for inspection and maintenance.

Power take-off (PTO) Subsystem
The purpose of this system is to convert efficiently the mechanical power developed by the hydrofoil system into electrical power, suitable for exporting to the electricity distribution network.

Installation and Maintenance Strategies
These are not subsystems but processes; they are however necessary for all devices and critical to the commercial success of a tidal stream power development. Important aspects of these processes include requirements for specialist vessels and equipment; time taken to install a unit; access to and/or recovery of the device and maintenance intervals.
APPLICATION

Stages and Gates

The Development Stages 1 to 3 entail mandatory testing and analytical requirements for the hydrodynamic and reaction subsystems, specified on pages 12-14, in conjunction with developer-defined Research and Development (R&D). The development stages used in this Protocol may be briefly summarized as follows:

**Stage 1**
- Explain concepts for the subsystems.
- List the major components.
- Identify R&D requirements for Stages 2-3, in addition to the minimum requirements specified below.
- Provide documentation for standard, off-the-shelf components used within their specification and not requiring further testing.

**Stage 2** Conduct physical tests at an intermediate scale and/or carry out CFD or other numerical simulation (where required – see pages 12-14).

**Stage 3** Conduct physical tests at a large scale, possibly with a degree of integration between some of the subsystems (where required – see pages 12-14).

**Stage 4** Full-scale prototype testing at sea.

**Stage 5** Full-scale commercial demonstrator testing.

The developmental stages and gates have been summarised in the form of a flowchart. Error! Reference source not found. shows the entire flowchart, without detail in the process and gate symbols. Figures 3 to 8 show the sub-flowchart detailing each individual stage. The processes are labelled according to Table 2. For example, label PrH3 refers to the set of processes of development of the Hydrodynamic subsystem at Stage 3. The labels correspond to those in the Report templates, which may be found in a separate report (Bahaj, Blunden and Anwar 2008b) so the reporting matches the
decision gates in the flowchart. Other terms used in the flowcharts are defined in Table 3.

### Table 2. Legend for flowchart labels

<table>
<thead>
<tr>
<th>Term</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr</td>
<td>Process of Development Stage</td>
</tr>
<tr>
<td>Ga</td>
<td>Gate</td>
</tr>
<tr>
<td>J</td>
<td>Jump</td>
</tr>
<tr>
<td>H</td>
<td>Hydrodynamic Subsystem</td>
</tr>
<tr>
<td>R</td>
<td>Reaction Subsystem</td>
</tr>
<tr>
<td>C</td>
<td>Control Subsystem</td>
</tr>
<tr>
<td>P</td>
<td>Power take-off Subsystem</td>
</tr>
<tr>
<td>Fs</td>
<td>Full-scale device</td>
</tr>
<tr>
<td>W</td>
<td>Whole System</td>
</tr>
<tr>
<td>[1-6]</td>
<td>Sub-flowchart</td>
</tr>
</tbody>
</table>

### Table 3. Terms used to describe hydrodynamic testing facilities

<table>
<thead>
<tr>
<th>Term</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermediate-sized</td>
<td>Not less than 1.6 m depth</td>
</tr>
<tr>
<td>facility</td>
<td></td>
</tr>
<tr>
<td>Large facility</td>
<td>Not less than 3.0 m depth</td>
</tr>
<tr>
<td>1/20 scale</td>
<td>Minimum 0.8 m equivalent diameter</td>
</tr>
<tr>
<td>1/10 scale</td>
<td>Minimum 1.5 m equivalent diameter</td>
</tr>
</tbody>
</table>

‘Equivalent diameter’ refers to the diameter of a circle with the same area as the flow capture area of the device.

It can be seen from Error! Reference source not found. that to progress from one development stage to the next, the system must first pass some subsystem technical readiness criteria. These gates are to ensure that the uncertainty in the predicted performance of the subsystems (or in the later stages, the integrated system) has been sufficiently reduced within that development stage.

If all the subsystems have reached the required technical readiness, then the whole system is then re-evaluated by the cost of energy model, which becomes more detailed at each stage. If the upper and lower estimates of the cost of energy are below the threshold values, then the system progresses to the next stage. If not, then the design may be modified, re-tested and re-assessed. Detailed price estimates for materials and components have not been included in this Protocol due to price variations with time and the wide variety of tidal-current energy conversion solutions to which this Protocol may be applied.
It should be noted that this flowchart description does not aim to reproduce the full complexity and iterative nature of the design and testing processes.
Defining R&D Requirements

The general principle applied in Stages 1-3 is that the testing requirements for technical readiness should be commensurate with the degree of novelty of the subsystems and their components. ‘Novelty’ is here defined as the extent to which the design of the subsystem components represents a significant departure from the body of existing knowledge within the offshore, marine and wind industries (and the tidal stream industry, once established), as encapsulated in established standards and guidelines, such as those listed in Appendix A.

In this Protocol, Research and Development requirements are formulated in Stage 1 and then refined in Stage 2. For the Hydrodynamic and Reaction subsystems, developers must as a minimum conduct testing as specified on pages 13-14. In conjunction, Developers must also define their own testing requirements for novel components and subsystems.

For components that are bought ‘off-the-shelf,’ intended for offshore use and are to be used within the manufacturer’s specification, clearly there is no requirement for further testing by the device developer. Off-the-shelf components used outside the envelope specified by the manufacturer will require testing, however. This category includes all components designed for land-based use. All Reaction subsystem components that were not designed for use in areas with strong tidal currents are classed as novel in application, even if designed for offshore use in general.

Equipment and procedures used in installation and maintenance of tidal stream devices may also fall into the category of ‘novel’ or ‘off-specification.’ Consequently, these important aspects of the overall system should be treated in the same way as subsystem components, with research and development requirements identified in Stage 1.
Minimum Hydrodynamic and Reaction Subsystem R&D Requirements

For the Hydrodynamic and Reaction subsystems, the Protocol specifies minimum research and development requirements. These vary depending on the configuration of the device to reflect the novelty of the proposed design. The requirements are stated below in flowchart form (Figure 2 and Figure 3). There is clearly overlap between the R&D requirements for these two subsystems; for example, the results of a BEM analysis might be input into a dynamic analysis of a floating reaction subsystem design.
Figure 2. Flowchart showing minimum analysis and testing requirements for Hydrodynamic Subsystem. *Requires justification in Stage 1 Report

Figure 3. Flowchart showing minimum analysis and testing requirements for Reaction Subsystem
Additional R&D Requirements for Novel Subsystems and Components

In Stage 1, once the minimum R&D requirements have been determined (see section above) and the major components of all the subsystems have been listed, for each major component, the developer has to determine whether:

1. The component design has been proven in an offshore environment and will be used within its specified design envelope, or it has been certified by a Recognized Classification Society (RCS) such as DNV or GL.
2. The component is novel and requires some form of testing and/or simulation, at Stages 2, 3 or both.
3. The component or subsystem cannot meaningfully be simulated or tested at anything other than full-scale due to scale effects, etc.

If (1) applies, then the developer must provide evidence to this effect, for example:
- RCS certificates
- Relevant standards conformed to
- Manufacturers’ data sheets
- Published technical reports or articles
- Completed laboratory test reports

If (3) applies, an explanation should be provided.

In the case of (2), testing requirements for Stages 2 and 3 should be specified. Possible options could include:
- Lab-scale tests of components
- Full-scale land based tests of subsystems
- Control system simulation
### Figure 4 Development flowchart – overview of Stages in Protocol

<table>
<thead>
<tr>
<th>HYDRODYNAMIC</th>
<th>REACTION</th>
<th>CONTROL</th>
<th>POWER TAKE-OFF</th>
<th>WHOLE SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRH1</td>
<td>PRR1</td>
<td>PCR1</td>
<td>PRP1</td>
<td>PRW1</td>
</tr>
<tr>
<td>GAH1</td>
<td>GAR1</td>
<td>GAC1</td>
<td>GAP1</td>
<td>GAW1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>J1</td>
</tr>
<tr>
<td>STAGE 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRH2</td>
<td>PRR2</td>
<td>PCR2</td>
<td>PRP2</td>
<td>PRW2</td>
</tr>
<tr>
<td>GAH2</td>
<td>GAR2</td>
<td>GAC2</td>
<td>GAP2</td>
<td>GAW2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>J2</td>
</tr>
<tr>
<td>STAGE 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRH3</td>
<td>PRR3</td>
<td>PCR3</td>
<td>PRP3</td>
<td>PRW3</td>
</tr>
<tr>
<td>GAH3</td>
<td>GAR3</td>
<td>GAC3</td>
<td>GAP3</td>
<td>GAW3</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>J3</td>
</tr>
<tr>
<td>STAGE 4</td>
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</tr>
<tr>
<td>PRFS4</td>
<td></td>
<td></td>
<td></td>
<td>PRW4</td>
</tr>
<tr>
<td>GAFS4</td>
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<td>GAW4</td>
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<td>J4</td>
</tr>
<tr>
<td>STAGE 5</td>
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</tr>
<tr>
<td>PRFS5</td>
<td></td>
<td></td>
<td></td>
<td>PRW2</td>
</tr>
<tr>
<td>GAFS5</td>
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<td></td>
<td>GAW5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PRODUCTION</td>
</tr>
</tbody>
</table>

**KEY**
- Pr=Process; Ga=Gate; J=Jump
- H=Hydrodynamic subsystem
- R=Reaction subsystem
- C-Control subsystem
- P=Power take-off subsystem
- FS=Full-scale device
- W=Whole system (installation, maintenance and cost of energy)
Figure 5. Stage 1 sub-flowchart: concept formulation and identification of R&D requirements
Figure 6. Stage 2 sub-flowchart: Subsystem testing at intermediate scale / numerical simulation. *Where required
Figure 7. Stage 3 sub-flowchart: subsystem testing at large scale. *Where required
Figure 8. Stage 4 sub-flowchart: Prototype testing

Full-scale performance in terms of energy capture and availability should be measured and reported according to EMRC standards, e.g. EMRC/ABPmer (2008), when the standards become effective.

- Re-apply Cost of Energy model using the actual capital and operational expenditure of the prototype, and the actual measured performance of the prototype.
Figure 9. Stage 5 sub-flowchart: Commercial demonstrator testing

**Commercial Demonstrator Device tested at sea**

Full-scale performance in terms of energy capture and availability should be measured and reported according to EMEC standards, e.g. EMEC/ABPmer (2008), when the standards become effective.

**SprF\(5\) - Commercial Demonstrator Device tested at sea**

- Continuous automatic operation for 90 days?
- 80% availability?

**SprW\(5\) - Re-apply Cost of Energy Model using the actual capital and operational expenditure and the actual measured performance of the commercial demonstrator**

**GrF\(5\)**

- Cost of Energy for 5 MW array 7 ± 1 p/kWh?

**GrW\(5\)**

- YES
  - Production
- NO
  - J\(4\)

...
**Reporting Test Results**

After Stages 2 and 3, relevant test results should be reported as evidence of increasing technical readiness. Specific guidance for reporting hydrodynamic test results are included on page 23. The results should also be fed into the developer’s techno-economic model to give an updated cost of energy for the device. After Stage 2, in the light of specified test results, further testing may be required at Stage 3, additional to that specified in Stage 1. Templates for reporting at all of the five stages are included in a separate document (Bahaj, Blunden and Anwar, 2008b).

**Existing Guidelines and Certification Schemes**

A list of relevant standards and codes of practice from the offshore, marine and wind industries, sorted by Subsystem, is included in Appendix A. No judgement is made as to the applicability of these standards to particular devices, but they do contain a wealth of useful information relevant to the design of the various subsystems.

Compliance with emerging guidelines and certification schemes developed by Recognized Classification Societies (RCS) may be taken as evidence that the subsystems and components have been ‘proven’ or ‘qualified’ for full-scale deployment. Such RCS guidelines include:

- DNV (2005) “Guidelines on design and operation of wave energy converters”

It should however be recognized that these schemes are still undergoing development and may presently lack data required for assessing risk.
Changes to Subsystem and Component Design

If, in the course of the development process, the designs of components or subsystems are changed to the extent that previous analyses or model testing carried out no longer applies, the relevant Stage must be repeated for that subsystem and the device reassessed against the Whole System criteria for that Stage.

Specific Guidance for Testing Hydrodynamic and Reaction Subsystems

Full definitions of relevant variables can be found in a companion report, Bahaj, Blunden and Anwar (2008a).

Hydrodynamic Subsystem Testing at 1/20 scale (pH2)

Where scale model testing has been specified, these tests should be conducted in a circulating water channel or a towing tank, of depth at least twice the vertical extent of the flow capture area (i.e. greater than 1.6 m). Blockage ratios higher than 20% should be avoided. The dependent variables are rotor thrust and torque, which should ideally be measured using a calibrated dynamometer mounted so that it experiences forces prior to any losses due to seals, bearings etc. The independent variables are the channel speed or carriage speed and the rotational speed of the output shaft. Additional independent variables may include the pitch angle of the blades or hydrofoils, the yaw angle of the rotor to the flow and the immersion of the blades/hydrofoils.

Care should be taken to measure the channel speed in a location or manner unaffected by the local flow profile around the model rotor. If a towing tank is used, the carriage must reach a steady speed for long enough so that the measured parameters reach a steady state (in a time-averaged sense) in order for repeatable measurements to be made.
The results should be non-dimensionalized into values of thrust coefficient, power coefficient and speed ratio and then plotted in a similar manner to Figure 10 and Figure 11, alongside numerical predictions for comparison. It is recommended that a minimum of ten measurement points be made for each $C_T$ or $C_P$ versus speed ratio curve. If the blockage ratio is greater than about 5%, the results should be corrected to free stream conditions using an empirical method such as described in Bahaj (2007a). If the torque (or power) is measured after mechanical (or electrical) losses, then the losses should be established experimentally and if any corrections are made to the results, they should be explicitly stated in the experimental write-up. Other details included in the report should include:

- The location and dimensions of the testing facility
- The test rig configuration
- The calibration of strain gauges and flow speed sensors
- The blockage ratio
- The immersion of the blades/hydrofoils
- Tabulated values of channel speed, speed ratio, thrust coefficient and power coefficient for each of the additional variables (pitch angle, rotor yaw angle and immersion depth)
- Any observations of cavitation

Full details of the experimental testing of a comparable device are given in Bahaj et al. (2005).

Figure 10. Power coefficient versus speed ratio for a 0.8 m diameter scale axial flow tidal turbine.
Figure 11. Thrust coefficient versus tip speed ratio for a 0.8 m diameter scale axial flow tidal turbine. Towing tank and cavitation results are represented by circles and crosses; two different numerical predictions are plotted as solid and dashed lines. Source: Bahaj et al. (2007b)

Hydrodynamic, Reaction and Control Subsystem testing at 1/10 scale (pH3 pR3 and pC3)
Where 1/10 scale testing has been specified, possible options for testing a large model at an acceptably low blockage ratio (less than 20%), are:

- Large towing tank with depth greater than twice the vertical extent of the flow capture area.
- Mounted in the headrace of a reservoir or other enclosed body of water
- Towed by a vessel
- Suspended beneath a moored pontoon or vessel in a tidal stream
- Attached to a dedicated mooring
- Mounted on the sea bed

The hydrodynamic and reaction subsystems should be geometrically similar to the full-scale prototype, as far as they may significantly interact and as dynamic scaling allows. The power take-off subsystem may be simulated by a suitable mechanical/electrical resistive load. In addition to thrust and torque measurements on the rotor, described for 1/20 scale, the support structure and at least one blade/hydrofoil should be instrumented with strain gauges. The model must be subject to flow reversal under closed-loop control. If the device is designed for variable orientation or with pitch-able blades, this functionality should, where possible, be implemented in the model, and the model should be operated with flow in both directions to investigate blade/structure interactions.
The reporting should be as for 1/20 scale, but also to include time series and spectral plots of normal forces and bending moments on the blades/hydrofoils, along with wave amplitude.

The response of the control system should be tested under the following scenarios, where applicable:

- Start up from parked state
- Response to ‘gust’ above rated speed
- Shedding load at steady speeds above rated
- Shut down from rated power to parked state while flow maintained at rated speed

The shaft power, shaft rotational speed and output power should be plotted against time.

As for 1/20 scale, numerical predictions should accompany all experimental data and be plotted on the same axes for comparison.

**CFD Analyses**

Where a CFD analysis is required in Stage 2, the following aspects should be addressed and reported on, where applicable:

- Name of code used
- Form of equations and solver used
- Treatment of turbulence and the free-surface
- Boundary conditions for cases considered
- General arrangement of mesh/grid
- Details of mesh/grid-independence study, with statistics of edge angles and lengths.
- Degree of convergence

Results of CFD simulations should be plotted alongside any scale model test results, in order to highlight discrepancies. Best practice guidelines for CFD are available online, for example:

- MARNET Best Practice Guidelines for Marine Applications of Computational Fluid Dynamics: https://pronet.wsatkins.co.uk/marnet/guidelines/guide.html
- European Thematic Network QNET-CFD: http://eddie.mech.surrey.ac.uk/
Economic Analysis Methodologies

It is envisaged in this Protocol that the device developers will produce their own cost of energy model specific to their system, making appropriate assumptions at each development Stage. The device developers will use their cost of energy model to produce upper and lower estimates of cost of energy. The system will then be assessed as shown in the flowcharts in Figures 1-6 in the rightmost column.

Economic analyses of the cost of energy produced by tidal-current energy converting devices have been previously published in the following reports, which may be used to help develop a cost model:

- Revision 2. EPRI Guideline. Economic Assessment Methodology for Tidal In-stream Power Plants. EPRI, 2006
- Black and Veatch and IT Power. The commercial prospects for tidal stream power. DTI, 2001

It is expected that cost of energy model will explicitly include estimates of at least the following:

- Capital investment, including
  - Development
  - Device components
  - Installation
  - Electrical connection
- Discount rate
- Annual operation and maintenance costs
- Decommissioning cost
- Annual energy yield and capacity factor
REFERENCES


APPENDIX A: EXISTING STANDARDS IN THE MARINE, OFFSHORE AND WIND SECTORS

The Standards are grouped under the relevant subsystems. All Standards are current at the time of writing.

**General criteria/Installation/Maintenance**

BS EN ISO 19901-1:2005
Petroleum and natural gas industries. Specific requirements for offshore structures. Metocean design and operating considerations

BS EN ISO 19901-5:2003
Petroleum and natural gas industries. Specific requirements for offshore structures. Weight control during engineering and construction

BS EN 50308:2004
Wind turbines. Protective measures. Requirements for design, operation and maintenance

BS EN 61400-1:2005
Wind turbines. Design requirements

IEC system for conformity testing and certification of wind turbines. Rules and procedures

PD CLC/TR 50373:2004
Wind turbines. Electromagnetic compatibility

Wind turbine generator systems. Lightning protection

**Hydrodynamic Subsystem**

BS ISO 3455:2007
Hydrometry. Calibration of current-meters in straight open tanks

BS EN ISO 3715-1:2004
Ships and marine technology. Propulsion plants for ships. Vocabulary for geometry of propellers

Hydrometric uncertainty guide
Full-scale structural testing of rotor blades

BS EN 60193:1999
Hydraulic turbines, storage pumps and pump-turbines. Model acceptance tests

**Reaction Subsystem**

BS 6349-1:2000
Maritime structures. Code of practice for general criteria

BS 6349-6:1989
Maritime structures. Design of inshore moorings and floating structures

BS EN ISO 12215-1:2000

BS EN ISO 12215-2:2002

BS EN ISO 12215-3:2002
Small craft. Hull construction and scantlings. Materials. Steel, aluminium alloys, wood, other materials

BS EN ISO 12215-4:2002
Small craft. Hull construction and scantlings. Workshop and manufacturing

BS EN ISO 12215-5:2008
Small craft. Hull construction and scantlings. Design pressures for monohulls, design stresses, scantlings determination

BS EN ISO 12215-6:2008
Small craft. Hull construction and scantlings. Structural arrangements and details

BS EN ISO 19901-2:2004
Petroleum and natural gas industries. Specific requirements for offshore structures. Seismic design procedures and criteria
BS EN ISO 19901-4:2003
Petroleum and natural gas industries. Specific requirements for offshore structures. Geotechnical and foundation design considerations

BS EN ISO 19901-7:2005
Petroleum and natural gas industries. Specific requirements for offshore structures. Stationkeeping systems for floating offshore structures and mobile offshore units

BS EN ISO 19902:2007
Petroleum and natural gas industries. Fixed steel offshore structures

BS EN ISO 19903:2006
Petroleum and natural gas industries. Fixed concrete offshore structures

BS EN ISO 19904-1:2006
Petroleum and natural gas industries. Floating offshore structures. Monohulls, semi-submersibles and spars

Wind turbines. Measurement of mechanical loads

**Control Subsystem**

BS EN 61400-25-1:2007
Wind turbines. Communications for monitoring and control of wind power plants. Overall description of principles and models

BS EN 61400-25-2:2007
Wind turbines. Communications for monitoring and control of wind power plants. Information models

BS EN 61400-25-3:2007
Wind turbines. Communications for monitoring and control of wind power plants. Information exchange models

BS EN 61400-25-5:2007
Wind turbines. Communications for monitoring and control of wind power plants. Conformance testing
**Power take-off Subsystem**

**BS ISO 13628-5:2002**  
Petroleum and natural gas industries. Design and operation of subsea production systems. Subsea umbilicals

**BS ISO 13628-11:2007**  
Petroleum and natural gas industries. Design and operation of subsea production systems. Flexible pipe systems for subsea and marine applications

**BS EN 61400-12-1:2006**  
Wind turbines. Power performance measurements of electricity producing wind turbines

**BS EN 61400-21:2002**  
Wind turbine generator systems. Measurement and assessment of power quality characteristics of grid connected wind turbines

**BS ISO 81400-4:2005**  
Wind turbines. Design and specification of gearboxes

**BS MA 18:1973**  
Specification for salt water piping systems in ships
APPENDIX B: WRITTEN COMMENTS RECEIVED ON THE DRAFT PROTOCOL

The comments are reproduced in full below. Responses to the comments are included inline (in bold).

I have an unusual viewpoint on this type of thing, as we have developed our concept from scratch, from outside a recognised company or university. This means that we have been obliged to go through the "gates" which have been placed in our way by the investment community. It seems clear to me that any framework should try to match these empirically derived gates, which have arisen because people will only put money forward once they are comfortable with the risk being presented.

As a general comment, I feel that this draft Protocol doesn't reflect what is required to raise capital to develop a novel idea. It should reflect what is needed to get an idea through to success starting from zero.

In order to get the cost of energy from tidal currents down to competitive levels, there has to be a lot of innovation. This Protocol would not allow anyone working outside an established company or university to develop a concept. It would therefore eliminate 99% of the possible sources of innovative ideas.

Stage 1 should be achievable by one determined person working with a great idea, a computer, and the internet. This individual can then use their compliance with stage 1 to show to strategic partners, / investors, that their idea is great, and that they know what they are doing.

Once an idea has been proved on paper, it should be possible to raise funding to research it properly. This stage has to be about gaining enough confidence in the concept to be able to raise the funding to build a big machine.

The next stage should be about gaining enough confidence to be able to raise funding to build a full scale machine.

The final stage is about building the commercial scale machine itself.

At each stage the commercial case, as well as the technical case must be made. The earliest stages should therefore also be about defining a commercial strategy, understanding the competition, and setting out how the concept is going to fill a
Response: The aim of the Protocol is not to assess the commercial strategy of the developer, but the technical readiness and cost of energy of the device that is being developed.

Response: In the revised version of the Protocol, it is made clear that the R&D requirements depend on the degree of novelty in the technologies employed in the subsystems.

Response: In the revised version of the Protocol, the availability requirements have been reduced to 60% and 80% respectively in stages 4 and 5.

gap in the competition.

Comments in detail:

Stage 1
This is too detailed. It should be about modelling the system and making cost estimates. Performance predictions, based on sound principles, and full parts list with costs against each of the parts.

Stage 2.
I think that guidance on the appropriate scale is useful. This looks like advising the miniaturisation of a full scale system, right down to using hydraulic actuators, cooling, and electrical equipment. I don't feel this is necessary, and feel that this stage should only be about confirming the predictions of the performance model. Generating electrical power at this stage will be expensive and unnecessary. The control equipment required to simulate a full scale system will be much too costly.

If confidence is gained in the mathematical model, the model can be used to simulate different control strategies.

Stage 3.
I question the point of this stage in the development process

Stage 4.
Full scale? It would be very difficult indeed to raise enough money to build a full scale system on the back of 1/10 scale testing. I don't think it would be possible with a particularly innovative idea. I think this should be 1/3 scale marine testing, or something similar, as Seaflow, Open Hydro and Pulse. Apart from this most of the items in the flow chart seem sensible. I don't think that 90% availability is a good idea. For the first test of a system in a fully marine environment, this is a tall order, and design issues may come to the fore which mean that this is impossible to meet without re-building the system.

Stage 5.
Fine. 95% availability? The first offshore wind farms didn't get any where near this.
APPENDIX C: NOTES FROM CONSULTATION WORKSHOP HELD AT BERR ON 11 JULY 2008.

Workshop attendees

Group 1
AEA Group Dr Howard Rudd
BERR Mr Trevor Ragatt
EMEC Mr Bill Edgar
Teamwork Technology & Dr Fred Gardner
Tocardo
University College, Cork Mr Brian Holmes
University of Edinburgh Professor Ian Bryden
University of Southampton Professor AbuBakr Bahaj
University of Southampton Mr Luke Blunden

Group 2
AEA Group Mr Toby Smith
BERR Mr Alan Morgan
Carbon Trust Mr Steve Wyatt
Marine Current Turbines Dr Peter Fraenkel
Strachan & Henshaw Mr Roger Taylor
Tidal Generation Ltd Mr Jeremy Thake
University of Southampton Dr Arif Anwar
University of Southampton Dr Luke Myers

Outline of the workshop

The Workshop was chaired by AbuBakr Bahaj (UoS) and began with a welcome from Trevor Raggatt (BERR). Howard Rudd (AEA Group) explained the context of the Protocol as an IEA-OES task, building on the HMRC Wave Device Protocol. AbuBakr Bahaj then introduced the draft document, explaining the scope and objectives of the Protocol. Arif Anwar (UoS) explained the overall approach taken in producing the draft, using TRA and stage-gate methodologies. Luke Blunden (UoS) explained the flowcharts used in the Protocol to illustrate the stages and gates. AbuBakr Bahaj introduced some key overall questions for the workshop, specifically:

Overall questions
1. How many development stages should be specified in the Protocol?
- Is it necessary to have two stages involving physical modelling?
- Can CFD simulations replace a physical modelling stage?

2. Where should the first stage begin:
   - At the purely conceptual level, or
   - After some design work has been completed?

3. How to take account of transfer of proven technology to tidal stream devices?
   - Concentrate the Protocol on novel aspects of technology?

4. Economics:
   - How detailed should the techno-economic assessment be at each stage, and
   - What values of projected p/kWh can be reasonably expected at each stage?

At this stage, some general questions were asked and points raised:
- How are installation and O&M costs to be taken into account in the economic assessment?
- How will the Protocol be used in practice?
- How does the Protocol relate to the EquiMar project?

The attendees then separated into two breakout groups, discussing in detail the following questions on scale model testing and on power take-off and control:

**Scale model testing**

1. What are the appropriate range of model scales or dimensions for testing?
   - E.g. 1:20 or ~1 m dia; 1:10 or ~2 m dia; larger?
2. Is model testing with combined waves and currents both practical and necessary?
   - Depends on the design?
3. What level of realism is required in physical modelling at each stage?
   - Simulated PTO and control subsystems?
4. What minimum levels of max(Cp) are reasonable for scale models (before losses)?
   - E.g. 0.25, 0.3?
5. How should the results be reported to the funding/assessing body?

**Power take-off and control**

1. At what stage should PTO and control be integrated into testing?
2. Can control system be adequately simulated numerically up to prototype stage?
3. Should full-scale land-based tests of the PTO subsystem be required?
4. What reporting should be required at each stage?
5. Should there be minimum criteria for power quality for commercial demonstrator stage (connected to electrical distribution network)?
   - E.g. refer IEC 61400-21 Measurement and assessment of power quality characteristics of grid connected wind turbines

The outcomes of the discussion were recorded on flipcharts and have been tabulated below. The workshop then broke for lunch, after which the breakout groups discussed in detail further questions on full-scale testing and the reaction subsystem:

**Full-scale testing**

1. How big is “full-scale?”
   - E.g. rated power > 100 kWe? Diameter > 3 m?
2. What should be the minimum length of deployment for prototype and commercial demonstrator models?
   - E.g. MRDF: “3 months continuously (except for planned shutdown) or 6 months cumulatively in any 12-month period”
3. What minimum levels of availability are reasonable?
   - 80%, 90%?
4. What values of Cpe should be achieved by prototype and commercial demonstrator models?
   - 0.25, 0.3?
5. How should incident velocity be measured?
   - E.g. refer EMEC “Performance Assessment for Tidal Energy Conversion systems (TECS) in Open Sea Test Facilities”

**Structures, moorings and foundations**

1. Under what circumstances is model testing necessary for ‘reaction subsystem’?
2. What are the main failure modes and load cases that should be considered?
   - or DNV (2005) “Guidelines on design and operation of wave energy converters”
3. What data should be required to generate representative fatigue load cases?
4. What evidence should be reported to the funding/assessing body?

As before, the outcomes of the discussion are tabulated below. After the breakout groups had completed their discussions, the two groups came back together to report the main points raised to the whole group. Howard Rudd summarized the outcomes from Group 1, followed by Arif Anwar for Group 2. AbuBakr Bahaj and Trevor Raggatt
thanked the attendees for their input and the workshop was closed.

Suggestions, questions and comments from the two breakout groups

The points raised are tabulated under the headings of the sets of questions asked of the breakout groups – scale model testing; power take-off and control; structures moorings and foundations and full-scale testing – plus a heading for general comments. The comments are also separated into the two groups in order to show the balance of opinion. The response of the authors to the comments is given below each set of comments (bulleted and in bold)

General comments

Group 1

G1.1 Add installability, durability and maintainability as criteria or ‘subsystems’ – these need to be taken account of in the design.

G1.2 Caveats (e.g. environmental assessment) need to be highlighted in the Protocol.

G1.3 The Protocol should provide guidance on reporting. Developers need to provide evidence that criteria have been met and their reporting should not include unsubstantiated claims.

G1.4 A standard template could be provided in the Protocol for reporting.

G1.5 Need to consider installability in design – hard to test or quantify.

G1.6 “Installability” should include whether the device can be installed in a small time-window.

- **The consensus at the workshop was that installability and maintainability are critical for tidal stream energy devices.** These factors relate to the system as a whole, so the economic criteria in the draft Protocol have been broadened in the revised Protocol to ‘whole system’ criteria to ensure that installability and maintainability are considered in the design.

- **Durability is a more general requirement of design and so remains under the separate subsystems.**

- **The caveats have been given more prominence in the revised version.**
A template for reporting at each stage has been produced and included in a separate document, to which the revised Protocol refers (Bahaj, Blunden and Anwar, 2008b).

**Group 2**

G2.1 The number of stages specified in the Protocol was considered reasonable.

G2.2 Installation, decommissioning, maintenance may be important in the economic analysis.

G2.3 The Protocol is biased in favour of turbines

G2.4 Development stages need not be overly prescriptive

G2.5 The conceptual model should also be subject to technical/economic evaluation

G2.6 Cost of energy might be better specified as range (+/-)

G2.7 Is a minimum value of cost of energy necessary?

G2.8 Is it possible to specify a generic input signal for use in economic analysis in the first three stages e.g. 3 m/s sinusoidal, but allow for exceptions?

G2.9 Maintenance, commissioning and decommissioning could be included in the Protocol as a separate subsystem, perhaps replacing the control subsystem.

- We accept that the hydrodynamic subsystem is given more prominence than the other subsystems in the Protocol, however most of the literature on tidal stream technology development focuses on this aspect of the design. It is also the subsystem that differs most from existing offshore, marine and wind technology. The Wave Protocol also focuses mainly on scale model testing.

- The cost of energy is now expressed as a range in the revised Protocol

- It is not possible to specify a generic tidal signal in the Protocol, as designs may vary depending on the velocities at the intended site or sites.

**Scale model testing**

**Group 1**

S1.1 Scale model testing should consider incorporating the effects of flow reversal and turbulence.

S1.2 If possible, testing should be done with waves as well as currents
S1.3 Could include scale model (3 m or 1/10) testing at sea or in a deep enough river, headrace of a lake or towing by a vessel.

S1.4 Include in the Protocol a list of available testing facilities, especially for waves and currents.

S1.5 PTO and control systems should be included when the model is “big enough so that it works.” i.e. > 1.5 m diameter.

S1.6 It is important to consider interactions between hydrodynamic and reaction subsystems, particularly when e.g. the turbine blades are in the wake of the structure. Model testing for this purpose needs to be large enough to be meaningful e.g. > 1.5 m

- Different possibilities for testing 1/10 scale models have been highlighted in the revised Protocol e.g. headrace, towing etc.
- Links to available online catalogues of testing facilities have been included in a separate document, to which the Protocol refers (Bahaj, Blunden and Anwar, 2008b). In addition are listed test facilities not included in the online catalogues.

**Group 2**

S2.1 Model testing with combined waves and currents not necessary.

S2.2 CFD shouldn’t be specified in the Protocol, although if it is undertaken, it could be evaluated by the ‘gates’

- In view of the disagreement between the two groups on the necessity or otherwise of model testing with waves, this has not been required in the Protocol, but advised where possible.
- CFD has been included as a possible option for Stage 2 R&D in the revised Protocol.

**Power take-off and control**

**Group 1**

P1.1 The control system can be numerically simulated – the Protocol should ask for an explanation of how the control system works.

P1.2 Whether land-based testing of the PTO is required by the Protocol depends on how innovative the subsystem is.

P1.3 There is no need for the Protocol to specify power quality criteria, as electricity distributors will demand this in any case. The Protocol may mention these requirements.
The reporting template included in a separate report (Bahaj, Blunden and Anwar, 2008b) includes questions relating to the Control Subsystem.

The revised Protocol makes it clearer in general that the degree of testing expected depends on the novelty of the technology or its application.

Numerical simulation of the control subsystem has been included as a possible option for Stage 2 R&D in the revised Protocol.

Power quality criteria have not been specified in the revised Protocol.

Full-scale testing

Group 1

F1.1 The meaning of ‘full-scale’ is related to the business model of the developer – i.e. what size do they plan to sell? Situation is complicated due to, for example multiple turbines per structure or mooring.

F1.2 Power production would be envisaged to be > 500 kW but smaller applications may be > 50 kW.

F1.3 Total electrical distribution network capacity requested/required by the developer may indicate the power generation potential e.g. > 1 MW.

F1.4 Operating period for full-scale demonstrator should be at least 3 months (same as MRDF).

F1.5 80% availability for demonstrator is reasonable.

F1.6 Global efficiency as defined in the Protocol should be ≥0.3 at rated.

F1.7 The incident velocity should be measured referring to EMEC standards.

No minimum power or size of turbine has been specified in the revised version, but the developer must state what “full-scale” means in the Stage 1 Report to avoid “changes of goalposts” later on.

EMEC standards for velocity measurement have been specified in the revised version.

The required length of deployment for the demonstrator has taken from MRDF and the availability has been defined more precisely and reduced to 80%.
Group 2

F2.8 There is a need to carefully define terminology: "demonstrator" vs. "prototype."

F2.8 The demonstrator should be 1:1 scale with the intended production model.

F2.9 The demonstrator should typically have a 3-month deployment period with a percentage set aside for maintenance.

- "Demonstrator" has been replaced with "Commercial demonstrator" in the revised version to prevent ambiguity with "Prototype."

Structures, moorings and foundations

Group 1

R1.1 ‘Stability’ should be added as a criteria of the reaction subsystem

R1.2 Testing requirements depend on design philosophy e.g. fixed or tethered.

R1.3 Applicability of design to different sea-bed types (e.g. rock, clay, sand...).

R1.4 Testing the reaction subsystem at model scale will be difficult.

R1.5 For failure modes refer to DNV & GL guidelines, recognizing that these are work in progress and that new approaches may be needed.

R1.6 Calculations need to recognize the existence of turbulence in the flow.

R1.7 Include scenarios of loading imposed by ‘variability of the environment’ (may be covered by the guidelines)

R1.8 Control system failure may be the most onerous failure mode.

- The revised Protocol will refer to the GL and DNV guidelines, whilst advising caution as these are still undergoing development. These guidelines do take account turbulence and environmental actions, so the Protocol does not need to cover them independently.

Group 2

R2.1 The load cases should be defined by the developer rather than specified in the Protocol.

- The Protocol does not specify particular load cases but does require consideration of relevant phenomena, such as fatigue, by referring to the guidelines mentioned in the response to R1.