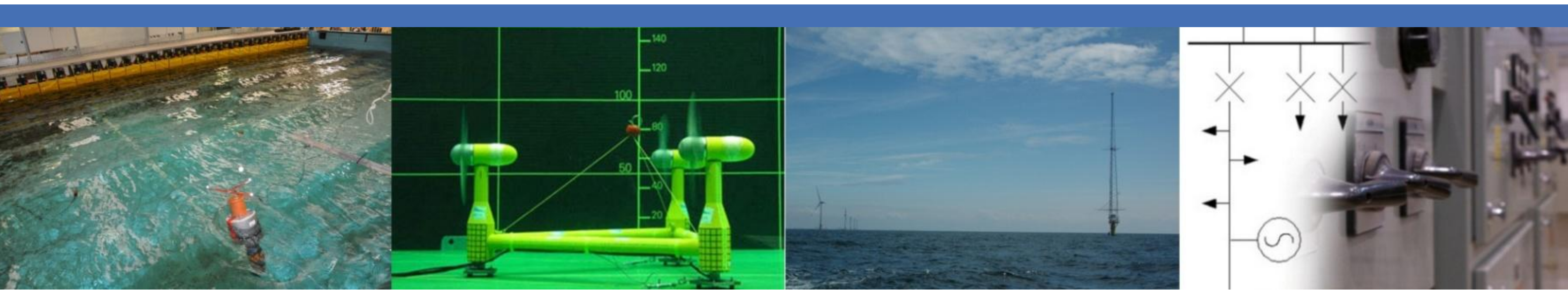
MARINET

Marine Renewables Infrastructure Network



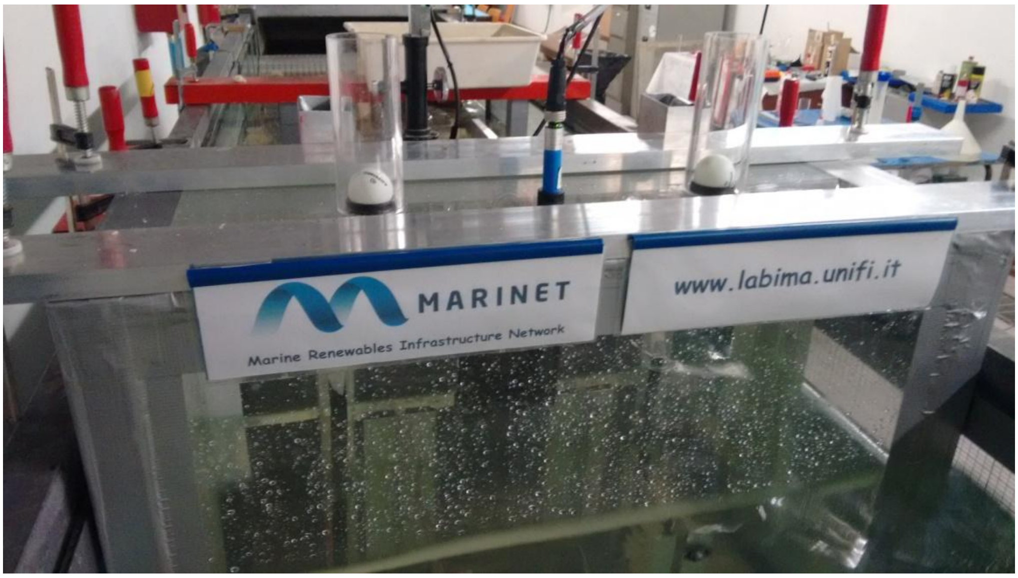
Infrastructure Access Report

Infrastructure: UNIFI-CRIACIV Wave-Current Flume

***User-Project*: [Insert the User-Project acronym]**

TESTING OF A CONCEPTUAL PRESURISED WATER COLUMN (PWC) AS A WAVE ENERGY CONVERTER (WEC)

CORES (Coastal Research & Engineering Centre), Bulgaria
Faculty of Engineering - University of Porto, Portugal
Technical University of Zagreb, Croatia
University of Architecture and Civil Engineering, Sofia, Bulgaria



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SEVENTH FRAMEWORK PROGRAMME

EC FP7 "Capacities" Specific Programme
Research Infrastructure Action

ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC's Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The aim of the initiative is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

Partners

Ireland
University College Cork, HMRC (UCC_HMRC)
Coordinator
Sustainable Energy Authority of Ireland (SEAI_OEDU)

Denmark
Aalborg Universitet (AAU)
Danmarks Tekniske Universitet (RISOE)

France
Ecole Centrale de Nantes (ECN)
Institut Français de Recherche Pour l'Exploitation de la Mer (IFREMER)

United Kingdom
National Renewable Energy Centre Ltd. (NAREC)
The University of Exeter (UNEXE)
European Marine Energy Centre Ltd. (EMEC)
University of Strathclyde (UNI_STRATH)
The University of Edinburgh (UEDIN)
Queen's University Belfast (QUB)
Plymouth University(PU)

Spain
Ente Vasco de la Energía (EVE)
Tecnalia Research & Innovation Foundation (TECNALIA)

Belgium
1-Tech (1_TECH)

Netherlands
Stichting Tidal Testing Centre (TTC)
Stichting Energieonderzoek Centrum Nederland (ECNeth)

Germany
Fraunhofer-Gesellschaft Zur Foerderung Der Angewandten Forschung E.V (Fh_IWES)
Gottfried Wilhelm Leibniz Universität Hannover (LUH)
Universitaet Stuttgart (USTUTT)

Portugal
Wave Energy Centre – Centro de Energia das Ondas (WavEC)

Italy
Università degli Studi di Firenze (UNIFI-CRIACIV)
Università degli Studi di Firenze (UNIFI-PIN)
Università degli Studi della Tuscia (UNI_TUS)
Consiglio Nazionale delle Ricerche (CNR-INSEAN)

Brazil
Instituto de Pesquisas Tecnológicas do Estado de São Paulo S.A. (IPT)

Norway
Sintef Energi AS (SINTEF)
Norges Teknisk-Naturvitenskapelige Universitet (NTNU)

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Infrastructure Accessed:	UNIFI-CRIACIV Wave-Current Flume
Infrastructure Manager (or Main Contact)	Prof. Lorenzo Cappietti

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02	08 Sept. 2015	Second version draft	Valeri Penchev	Lorenzo Cappietti	Final

About This Report

One of the requirements of the EC in enabling a user group to benefit from free-of-charge access to an infrastructure is that the user group must be entitled to disseminate the foreground (information and results) that they have generated under the project in order to progress the state-of-the-art of the sector. Notwithstanding this, the EC also state that dissemination activities shall be compatible with the protection of intellectual property rights, confidentiality obligations and the legitimate interests of the owner(s) of the foreground.

The aim of this report is therefore to meet the first requirement of publicly disseminating the knowledge generated through this MARINET infrastructure access project in an accessible format in order to:

- progress the state-of-the-art
- publicise resulting progress made for the technology/industry
- provide evidence of progress made along the Structured Development Plan
- provide due diligence material for potential future investment and financing
- share lessons learned
- avoid potential future replication by others
- provide opportunities for future collaboration
- etc.

In some cases, the user group may wish to protect some of this information which they deem commercially sensitive, and so may choose to present results in a normalised (non-dimensional) format or withhold certain design data – this is acceptable and allowed for in the second requirement outlined above.

Acknowledgement

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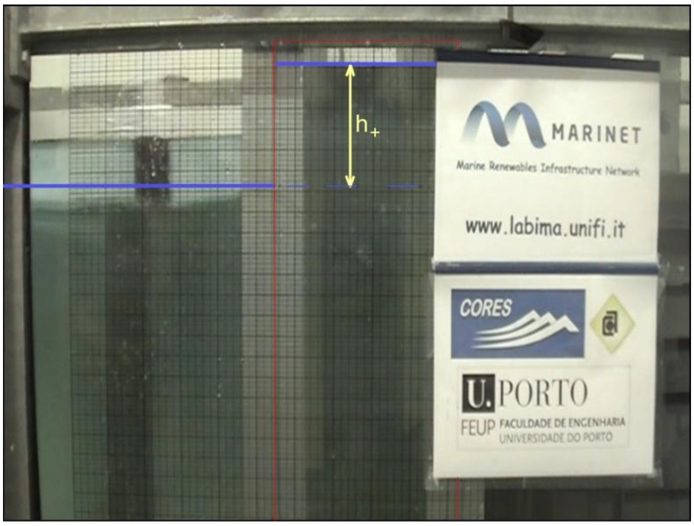
EXECUTIVE SUMMARY

A conceptual Pressurized Oscillating Water Column (POWC) has been tested in the UNIFI-CRIACIV Wave-Current Flume as a wave energy converter. The POWC concept suggests that the wave motion in a chamber equipped with a system of one-way (check) valves will allow water oscillation up - but shall restrict water movement down - and thus will generate a hydraulic head, supported by the vacuum pressure into the chamber. Furthermore a low-head turbine connected with the chamber can be used to generate electricity when the air valve is open and the pressure in the box is equal to the atmospheric one. At tidal seas the wave-driven water elevation can be superimposed to the high tide level, thus providing additional power potential. The system has the advantage to accumulate the power, and use it when necessary.

Participant from 4 research organisations from 3 EU countries – Bulgaria, Croatia and Portugal have been involved. Tests have been carried in the period 22 June – 4 July 2015. Main objective was to check the above concept, and provide some basic data for further numerical modelling. Test programme included tests under regular and irregular waves. The main conclusion was that a very good progress was made in light of clarifying the concept of the POWC. However further studies were recommended, in particular concerning modification and optimisation of the system for practical use of the generated hydraulic head.



CONTENTS

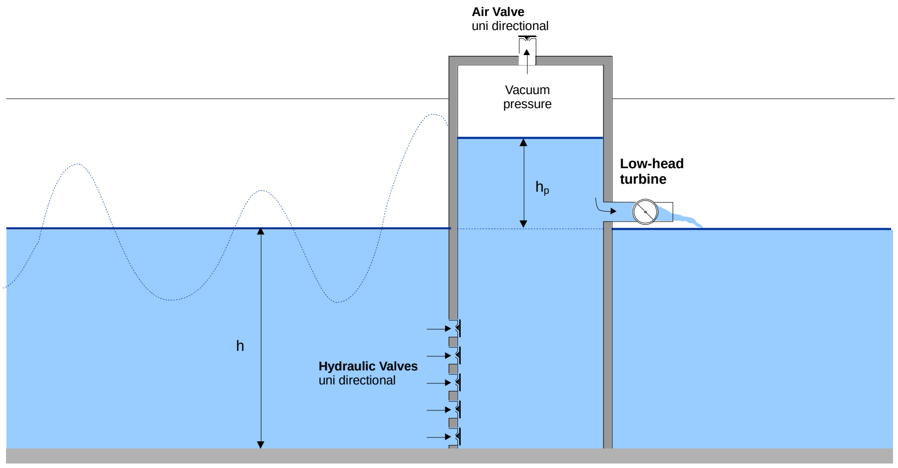
1 INTRODUCTION & BACKGROUND

1.1 INTRODUCTION

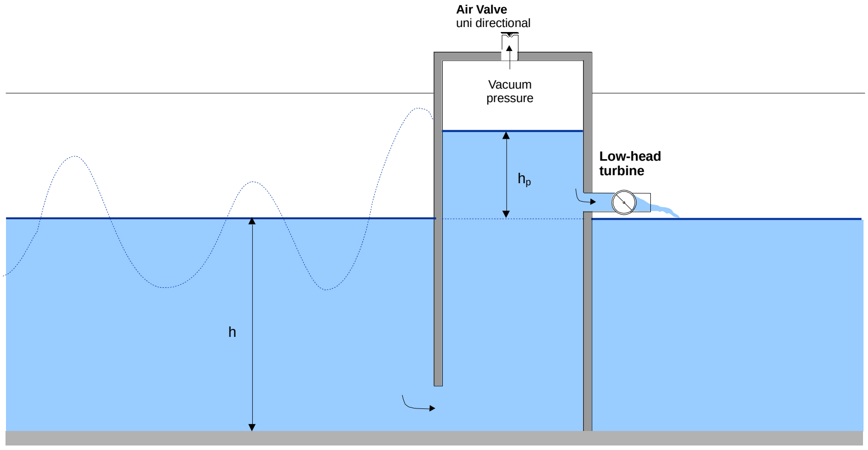
The concept of the POWC Pressurized Oscillating Water Column (POWC) as a WEC suggests that the wave motion in a chamber equipped with a system of one-way (check) valve(s) can restrict water movement down, and thus generate a water column supported by the vacuum into the box. Furthermore a low-head turbine can be placed above the mean sea level (Figure 1.a), and used to generate electricity when the air valve is open and the pressure in the box is equal to the atmospheric one. The system has the advantage to accumulate the power, and use it when necessary.

The height of the water column will be proportional to the significant wave height H_s, however it will also depend on mean wave period, and of the geometry/shape of the box. The discharge through the outlet (turbine) will be highly dependable on the hydraulic head and the amount of accumulated water. Wave generated water elevation can be superimposed to high tide level (at tidal coasts), thus providing additional power potential.

For the current tests, in order to simplify the model, the system of hydraulic valves can be replaced by an open aperture, assuming that the effect of different resistance on the generated hydraulic head h_p can be neglected.



a) General concept model



b) Simplified model

Figure 1. Concept of a POWC

Objectives of the test were:

- To check and prove the basic concept of a POWC
- To provide basic measurement data upon the height of the water column in the chamber as a function of H_s, and peak wave period
- To provide measurement data upon various discharges (l/s) through the outlet as a function of H_s (and peak wave period)
- To provide comparative measurement data for the case of an Alternative OWC (AOWC) generating a hydraulic head at normal - atmospheric pressure .
- To provide a data set for validation of a further CFD model, to study and compare power potential of both POWC and AOWC.

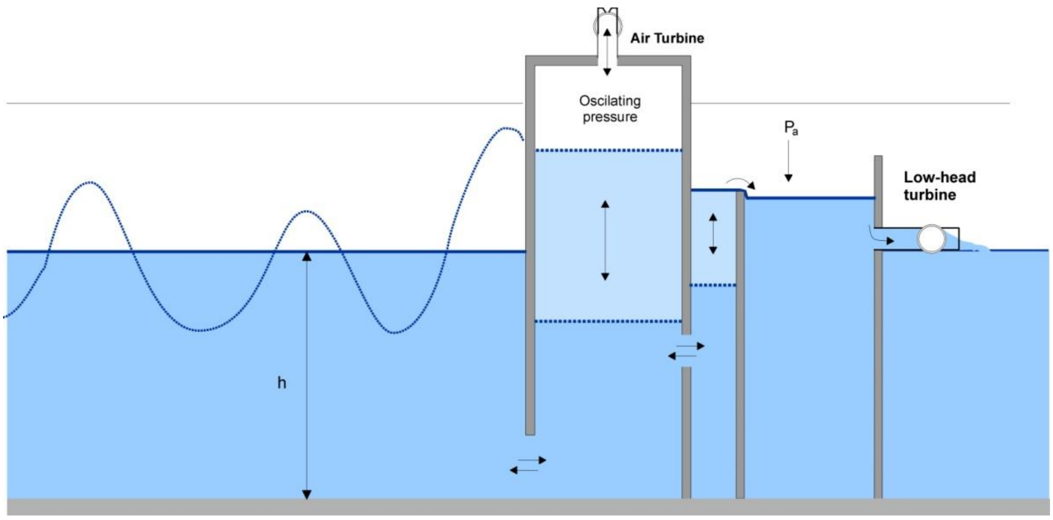


Figure 2: AOWC (Alternative OWC) generating a hydraulic head at atmospheric pressure (comparison vs POWC)

1.2 Development So Far

1.2.1 Stage Gate Progress

Previously completed: ✓
Planned for this project: ➲

STAGE GATE CRITERIA	Status
Stage 1 – Concept Validation	
• **Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)**	➲
• **Finite monochromatic waves to include higher order effects (25 –100 waves)**	
• **Hull(s) sea worthiness in real seas (scaled duration at 3 hours)**	
• **Restricted degrees of freedom (DofF) if required by the early mathematical models**	
• **Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)**	
• **Investigate physical process governing device response. May not be well defined theoretically or numerically solvable**	➲
• **Real seaway productivity (scaled duration at 20-30 minutes)**	
• **Initially 2-D (flume) test programme**	➲
• **Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them**	
• **Evidence of the device seaworthiness**	
• **Initial indication of the full system load regimes**	➲
Stage 2 – Design Validation	
• Accurately simulated PTO characteristics	
• Performance in real seaways (long and short crested)	
• Survival loading and extreme motion behaviour.	
• Active damping control (may be deferred to Stage 3)	
• Device design changes and modifications	
• Mooring arrangements and effects on motion	
• Data for proposed PTO design and bench testing (Stage 3)	
• Engineering Design (Prototype), feasibility and costing	
• Site Review for Stage 3 and Stage 4 deployments	
• Over topping rates	
Stage 3 –Sub-Systems Validation	
• To investigate physical properties not well scaled & validate performance figures	
• To employ a realistic/actual PTO and generating system & develop control strategies	
• To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag	
• To validate electrical supply quality and power electronic requirements.	
• To quantify survival conditions, mooring behaviour and hull seaworthiness	
• Manufacturing, deployment, recovery and O&M (component reliability)	
• Project planning and management, including licensing, certification, insurance etc.	
Stage 4 – Solo Device Validation	
• Hull seaworthiness and survival strategies	

STAGE GATE CRITERIA	Status
• Mooring and cable connection issues, including failure modes	
• PTO performance and reliability	
• Component and assembly longevity	
• Electricity supply quality(absorbed/pneumatic power-converted/electrical power)	
• Application in local wave climate conditions	
• Project management, manufacturing, deployment, recovery, etc	
• Service, maintenance and operational experience [O&M]	
• Accepted EIA	
Stage 5 – Multi-Device Demonstration	
• Economic Feasibility/Profitability	
• Multiple units performance	
• Device array interactions	
• Power supply interaction & quality	
• Environmental impact issues	
• Full technical and economic due diligence	
• Compliance of all operations with existing legal requirements	

1.2.2 Plan For This Access

The following plan for this access was envisaged, corresponding to **Stage 1: Concept Validation**:

- Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves): **yes**
- Finite monochromatic waves to include higher order effects (25 –100 waves): **yes**
- Hull(s) sea worthiness in real seas (scaled duration at 3 hours): **n.a.**
- Restricted degrees of freedom (DofF) if required by the early mathematical models: **n.a.**
- Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning): **n.a.**
- Investigate physical process governing device response. May not be well defined theoretically or numerically solvable: **yes**
- Real seaway productivity (scaled duration at 20-30 minutes): **yes**
- Initially 2-D (flume) test programme: **yes**
- Short crested seas: **no**
- Evidence of the device seaworthiness: **provided by irregular wave tests**
- Initial indication of the full system load regimes: **provided by irregular wave tests**

2 OUTLINE OF WORK CARRIED OUT

2.1 INTRODUCTION

Tests have been carried in the wave-current flume of UNIFI-CRIACIV, Florence, Italy, in the period 22 June – 4 July 2015.

Participant from 4 research organisations have been involved, as shown above.

2.2 OBJECTIVES

Objectives of the test were:

To provide some basic measurement data upon the height of the water column in the chamber (hydraulic head) as a function of H_s, and peak wave period, as well as to measure relevant discharge (l/s) through the outlet, in order to:

1) test a conceptual POWC in order to check the basic concept of generating hydraulic head using one-way valve system and generated vacuum pressure
2) Compare measurement data for the case of an Alternative OWC (AOWC) generating a hydraulic head at normal - atmospheric pressure (without any valve system)
3) Pprovide a data set for validation of a further numerical (CFD) model, to study and compare power potential of both POWC and AOWC.

Tested models

CONFIGURATION	DESCRIPTION
PWC	The two air valves, on top of the model, are operating and the outflow pipe positioned on the rear of the model is closed. The air valve diameter is 3.6cm while the outflow pipe diameter is 2.0cm. The water depth in the flume is 55.0cm. The geometrical characteristics of the model are depicted in *Figure* 2
PWC_1	The two air valves, on top of the model, are always open and the outflow pipe positioned on the rear of the model is open. The air valve diameter is 3.6cm while the outflow pipe diameter is 2.0cm. The water depth in the flume is 55.0cm. The geometrical characteristics of the model are depicted in *Figure* 2 Water level in the channel equal to 55,0cm.

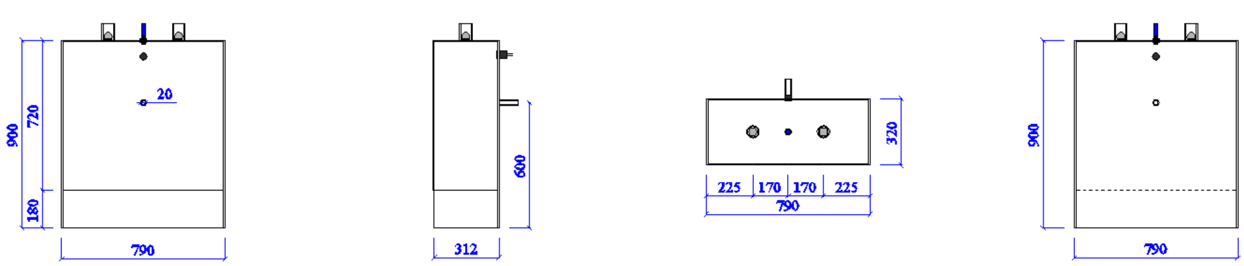


Figure 3- Configuration PWC & PWC_1: i) Front view ii) Side view iii) Plan view iv) Rear view

PWC_2	Same as the configuration PWC except the presence of the three openings on the frontal wall as depicted in *Figure* 3.
PWC_3	Same as the configuration PWC1 except the presence of the three openings on the frontal wall as depicted in *Figure* 3.

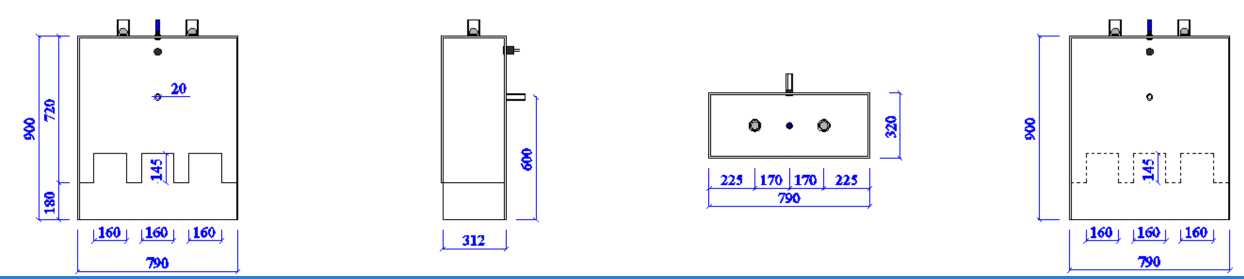


Figure 4 – Configuration PWC_2 & PWC_3: i) Front view ii) Side view iii) Plan view iv) Rear view

PWC_4	A second chamber is added behind the first. This second chamber is hydraulically

SEVENTH FRAMEWORK PROGRAMME

	connected to the first one by means of two circular openings (diameter 6.2cm) sited below the surface level. Moreover the absence of the roof on the second chamber assures that its free surface is subjected to the atmospheric pressure. A outflow pipe is positioned on the rear face of the second chamber (diameter 4.5cm) as depicted in *Figure* . The two air valves on the roof of the first chamber are always open. Water level in the channel equal to 55,0cm. Note that the probe WG4 is positioned in the second chamber.
PWC_5	Same as PWC_4 but the water level in the channel equalled 58,0cm.
PWC_6	Same as PWC_4 but the water level in the channel equalled 59,0cm.

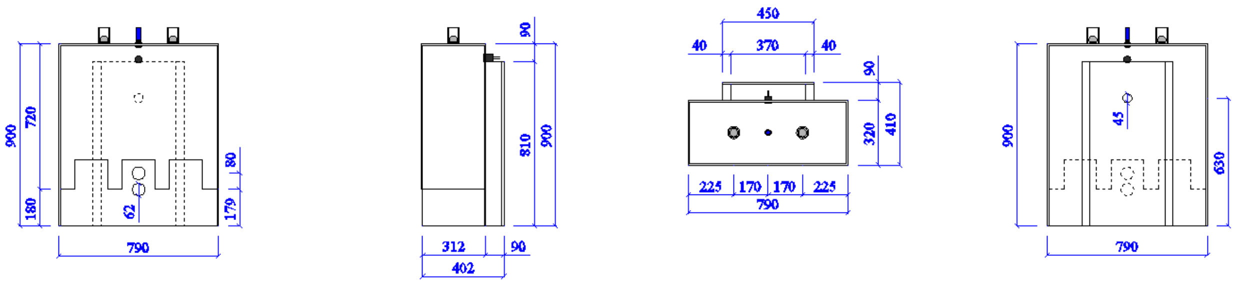
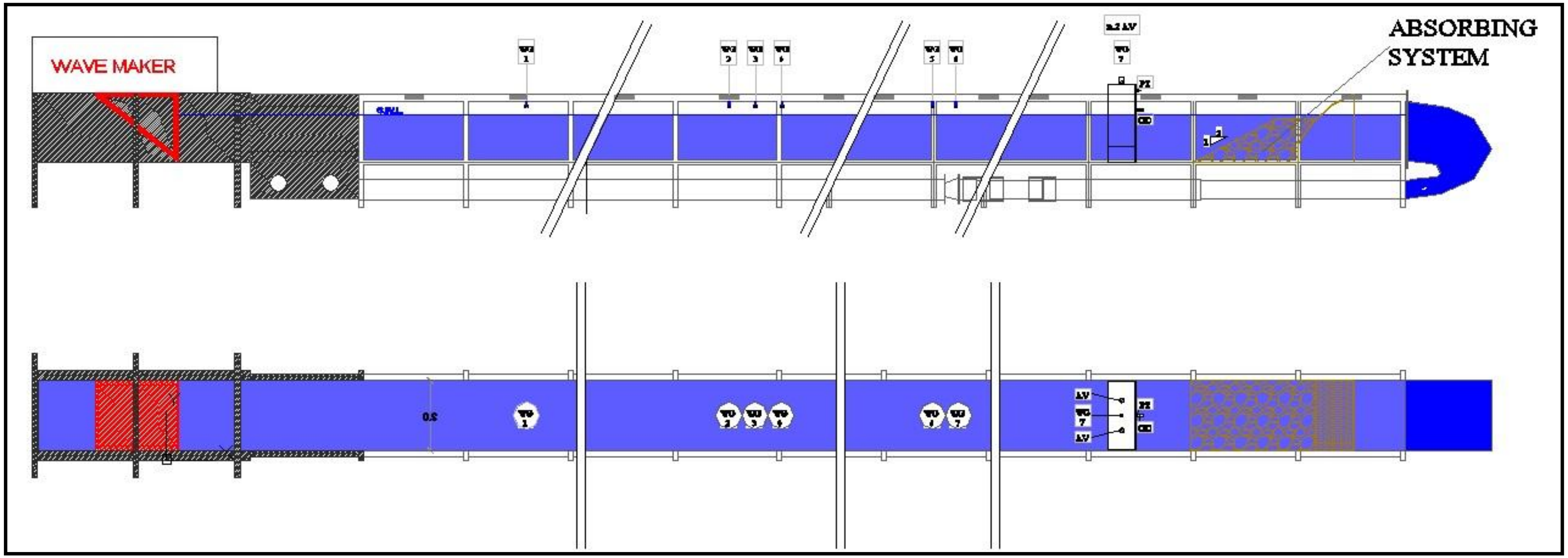


Figure 5 – Configuration PWC_4, PWC_5 & PWC_6: i) Front view ii) Side view iii) Plan view iv) Rear view

2.3 WAVE FLUME SETTING

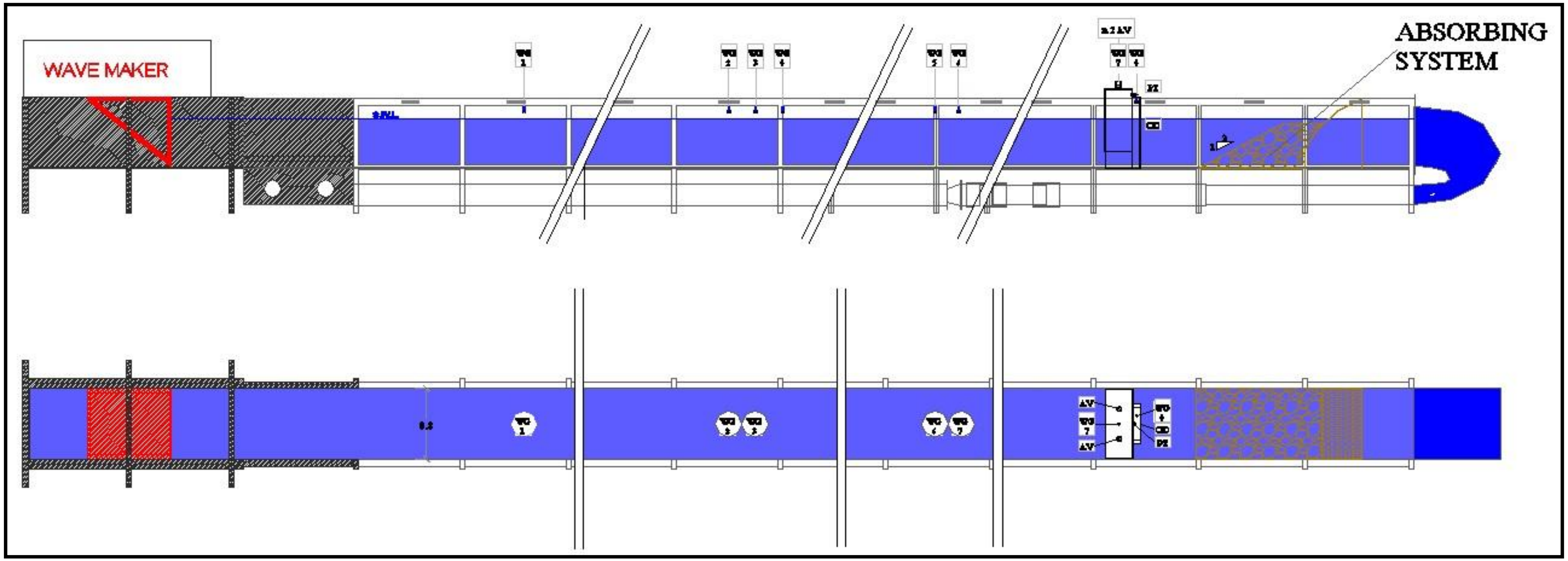
2.3.1 PWC – PWC_1 – PWC_2 – PWC_3



LEGEND:

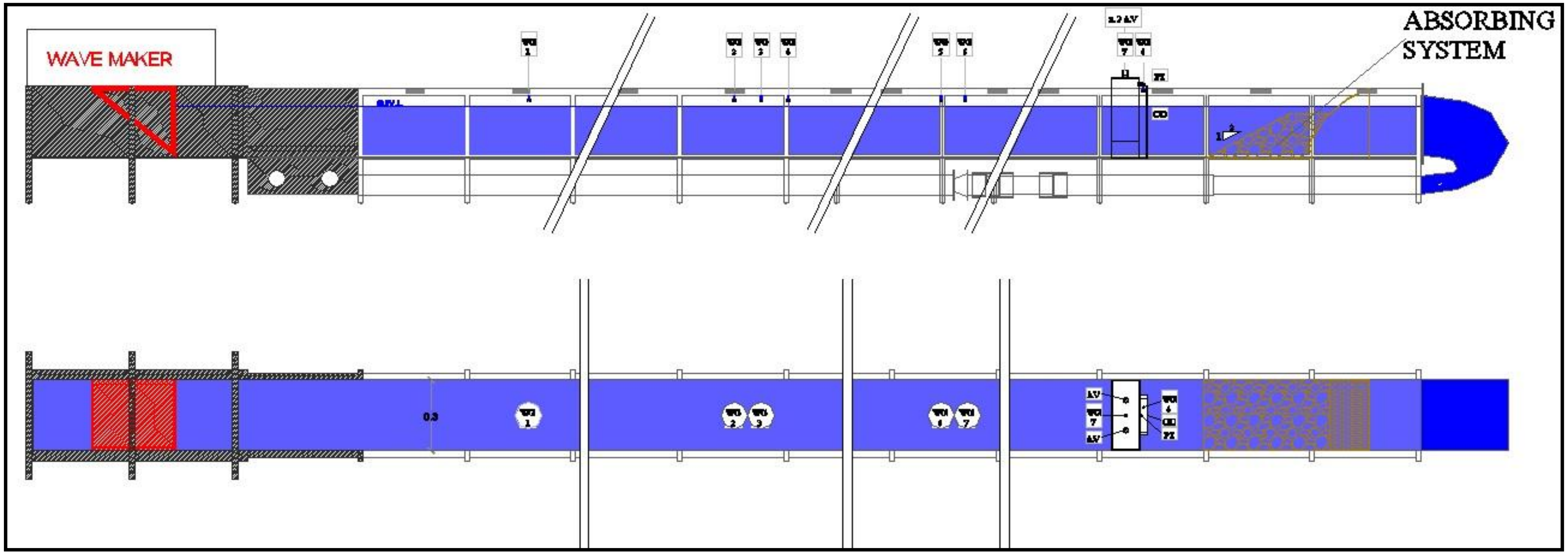
WG: Ultrasonic level probe
PT: Pressure transducer
AV: Air valve
OD: Output discharge

2.3.2 PWC_4



LEGEND:
WG: Ultrasonic level probe
PT: Pressure transducer
AV: Air valve
OD: Output discharge

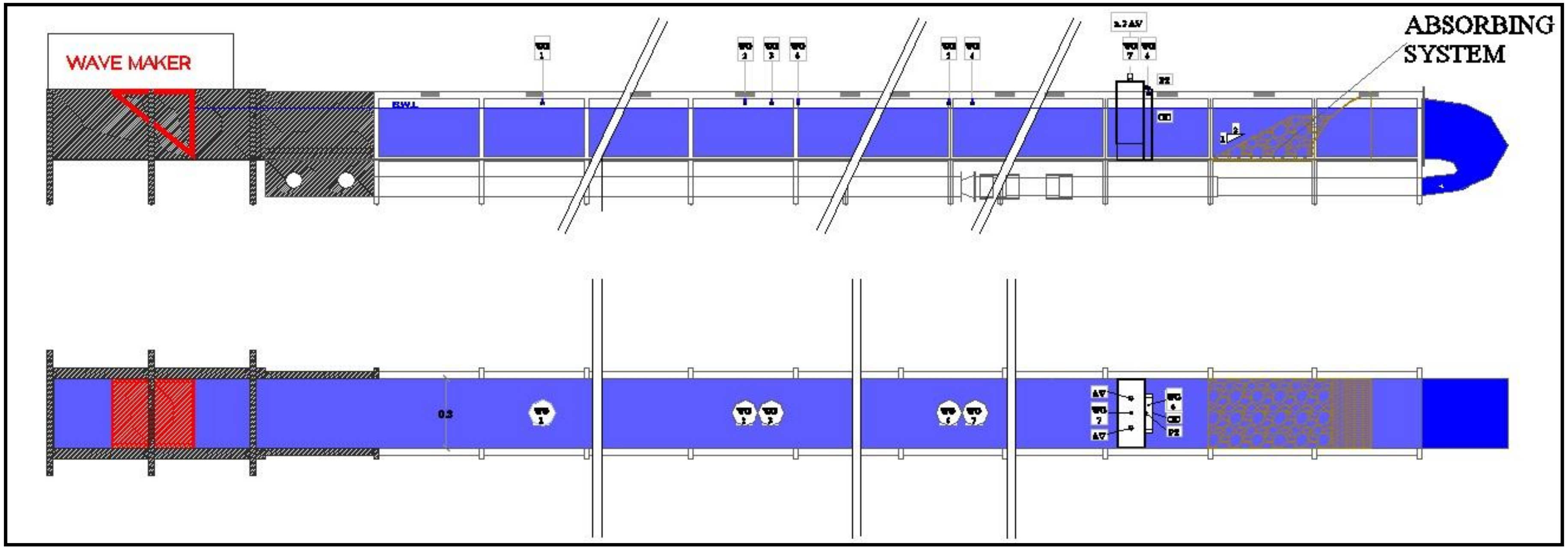
2.3.3 PWC_5



LEGEND:

WG: Ultrasonic level probe
PT: Pressure transducer
AV: Air valve
OD: Output discharge

2.3.4 PWC_6



LEGEND:

WG: Ultrasonic level probe
PT: Pressure transducer
AV: Air valve
OD: Output discharge

2.4 Positioning Equipment

- 1 hydrometric tip positioned 1.82m far from the Wavemaker;
- 1 camera positioned in front of the models;
- 1 camera positioned on the side of the models;
- 7 ultrasonic distance sensors positioned as summarized in table 1 (see Figure 6);
- 1 pressure transducer to measure the air pressure of the internal air volume (see Table 2 and Figure)

Table 1 - Distances of the ultrasonic distance sensors

NAME	Distance from the wavemaker [m]	Relative distances [m]
WG1	4.00	4.00
WG2	18.35	14.35
WG3	18.66	0.31
WG4	18.96	0.31
WG5	24.93	5.97
WG6	25.20	0.27
WG7 – on the models' roof	31.34	6.14

Max. sensing distance:	500 mm
Min. sensing distance:	60 mm
Switching frequency:	100 ms
Repeatability:	0,2 % or ±1 mm

OUTPUT	TERMINATION	REFERENCE
0-10 V	Connector	943-F4V-2D-1C0-330E
0-10 V	Cable	943-F4Y-2D-1C0-330E
4-10 mA	Connector	943-F4V-2D-1D0-330E
4-20 mA	Cable	943-F4Y-2D-1D0-330E

Figure 6 - Ultrasonic distance sensor HONEYWELL Series 943-M18 F4V-2D-1C0-330E. Picture and technical data sheet.

Table 2 - Distance of the pressure transducer from wavemaker and calibration curve.

NAME	Distance from wavemaker [m]	Calibration curve
PT	31.50	Y [**mbar**] = 13.347X [**V**] – 25.476

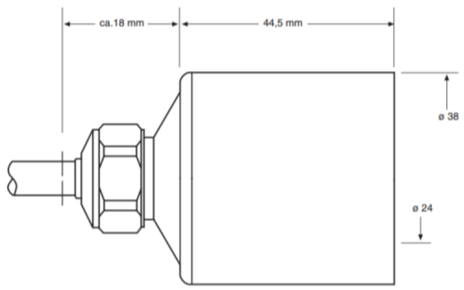


Figure 7 – Relative pressure transducer- KELLER Series 46X. Picture and technical drawing.

2.5 Tested Waves

Table 3 – Characteristic parameters and duration waves as measured by WG1.

REGULAR WAVES H and T values have been measured as mean values in the time window starting at 20s and ending at 30s			
CODE	**H [cm]**	**T [s]**	**Measurement time** [s]**
H01	8.5	1.5	80 s
H02	11.5	1.5	80 s
H03	14.0	1.5	80 s
H04	11.2	1.1	80 s
H05	16.0	1.8	80 s
H06	16.5	1.5	80 s
H07	15.0	2.1	80 s
IRREGULAR WAVES ($\gamma_{Jonswap}$ = 3.3) H and T values have been measured as mean values in the time window starting at 20s and ending at 50s			
CODE	**H [cm]**	**T [s]**	**Duration [s]**
H1*	12.5	1.5	80 s

* The irregular wave attack has been repeated 5 times. Each repetition has been characterized by the same spectral shape but a different time series.

** The 80 s of measurement time is composed by: 10 s with wave maker at rest (pre-trigger), 35 s of wave generation, 35 s of wave maker at rest (post-trigger).

2.6 CONDUCTED TESTS

Table 4 – Conducted tests

CONFIGURATION	WAVE	S.W.L.	DATE	Measurements FILE
PWC	H01	+55.0cm	26-06-2015	H01PWC.tsv
	H02	+55.0cm	26-06-2015	H02PWC.tsv
	H03	+55.0cm	26-06-2015	H03PWC.tsv
	H04	+55.0cm	29-06-2015	H04PWC.tsv
	H05	+55.0cm	29-06-2015	H05PWC.tsv
	H06	+55.0cm	26-06-2015	H06PWC.tsv
	H07	+55.0cm	26-06-2015	H07PWC.tsv
	H1sid1	+55.0cm	26-06-2015	H1-sid1PWC.tsv
	H1sid2	+55.0cm	26-06-2015	H1-sid2PWC.tsv
	H1sid3	+55.0cm	26-06-2015	H1-sid3PWC.tsv
	H1sid4	+55.0cm	29-06-2015	H1-sid4PWC.tsv
	H1sid5	+55.0cm	29-06-2015	H1-sid5PWC.tsv
PWC_1	H01	+55.0cm	29-06-2015	H01PWC_1.tsv
	H02	+55.0cm	29-06-2015	H02PWC_1.tsv
	H03	+55.0cm	29-06-2015	H03PWC_1.tsv
	H04	+55.0cm	29-06-2015	H04PWC_1.tsv
	H05	+55.0cm	29-06-2015	H05PWC_1.tsv
	H06	+55.0cm	29-06-2015	H06PWC_1.tsv
	H07	+55.0cm	29-06-2015	H07PWC_1.tsv
PWC – PWC_1	Resonance test	+55.0cm	26-06-2015	ResonanceTest_PWC.tsv
PWC_2	H01	+55.0cm	30-06-2015	H01PWC_2.tsv
	H02	+55.0cm	30-06-2015	H02PWC_2.tsv
	H03	+55.0cm	30-06-2015	H03PWC_2.tsv
	H04	+55.0cm	30-06-2015	H04PWC_2.tsv
	H05	+55.0cm	30-06-2015	H05PWC_2.tsv
	H06	+55.0cm	30-06-2015	H06PWC_2.tsv
	H07	+55.0cm	30-06-2015	H07PWC_2.tsv
PWC_3	H01	+55.0cm	30-06-2015	H01PWC_3.tsv
	H02	+55.0cm	30-06-2015	H02PWC_3.tsv
	H03	+55.0cm	30-06-2015	H03PWC_3.tsv
	H04	+55.0cm	30-06-2015	H04PWC_3.tsv
	H05	+55.0cm	30-06-2015	H05PWC_3.tsv
	H06	+55.0cm	30-06-2015	H06PWC_3.tsv
	H07	+55.0cm	30-06-2015	H07PWC_3.tsv
PWC_2 – PWC_3	Resonance test	+55.0cm	29-06-2015	ResonanceTest_PWC_2.tsv
PWC_4	H01	+55.0cm	02-07-2015	H01PWC_4.tsv
	H02	+55.0cm	02-07-2015	H02PWC_4.tsv
	H03	+55.0cm	02-07-2015	H03PWC_4.tsv
	H04	+55.0cm	02-07-2015	H04PWC_4.tsv
	H05	+55.0cm	02-07-2015	H05PWC_4.tsv
	H06	+55.0cm	02-07-2015	H06PWC_4.tsv
	H07	+55.0cm	02-07-2015	H07PWC_4.tsv
PWC_5	H01	+58.0cm	02-07-2015	H01PWC_5.tsv
	H02	+58.0cm	02-07-2015	H02PWC_5.tsv

	H03	+58.0cm	02-07-2015	H03PWC_5.tsv
	H04	+58.0cm	02-07-2015	H04PWC_5.tsv
	H05	+58.0cm	02-07-2015	H05PWC_5.tsv
	H06	+58.0cm	02-07-2015	H06PWC_5.tsv
	H07	+58.0cm	02-07-2015	H07PWC_5.tsv
PWC_6	H01	+59.0cm	02-07-2015	H01PWC_6.tsv
	H02	+59.0cm	03-07-2015	H02PWC_6.tsv
	H03	+59.0cm	03-07-2015	H03PWC_6.tsv
	H04	+59.0cm	03-07-2015	H04PWC_6.tsv
	H05	+59.0cm	03-07-2015	H05PWC_6.tsv
	H06	+59.0cm	03-07-2015	H06PWC_6.tsv
	H07	+59.0cm	03-07-2015	H07PWC_6.tsv

Format of the file that contains the measurements:

- First line -> header
- First column -> Date and Time
- Second column -> Paddle displacement [mm]
- Third to Ninth column -> ultrasonic distance sensors [mm]
- Tenth column -> Pressure transducer [V]

Pay attention to:

i. The acquisition frequency is equal to 20Hz.
ii. Each ultrasonic distance sensors measurement is the distance from the sensor tip to the free surface; it gives zero at sensor tip and the z axis is downlooking;
iii. The values acquired from the pressure transducer are in electrical units [V] and need to be processed in units of pressure [mbar] applying the calibration curve shown previously.

%Time	Paddle Displacement	WG1	WG2	WG3	WG4	WG5	WG6	WG7-PWC	PT
30/06/2015 21.46.35.862	-0.0145248	229.023	211.991	204.581	225.787	220.539	237.208	275.967	1.92286
30/06/2015 21.46.35.912	-0.0145012	229.027	212.013	204.575	225.765	220.537	237.103	276.005	1.92297
30/06/2015 21.46.35.962	-0.0144411	229.014	211.979	204.575	225.855	220.545	237.029	275.982	1.92297
30/06/2015 21.46.36.012	-0.0144144	229.075	211.986	204.591	225.821	220.537	237.028	276.01	1.92289
30/06/2015 21.46.36.062	-0.0144888	229.009	211.993	204.679	225.841	220.558	237.047	275.893	1.92278
30/06/2015 21.46.36.112	-0.0145254	229.107	211.957	204.594	225.89	220.538	237.065	275.999	1.92284
30/06/2015 21.46.36.162	-0.0144781	229.007	211.881	204.566	225.956	220.55	237.048	275.966	1.92292
30/06/2015 21.46.36.212	-0.0144373	229.03	211.979	204.569	225.879	220.489	237.076	276.03	1.923
30/06/2015 21.46.36.262	-0.0144176	228.996	211.967	204.558	225.849	220.522	237.021	275.936	1.9229
30/06/2015 21.46.36.312	-0.0145231	229.01	211.998	204.551	225.746	220.558	237.075	275.945	1.92295
30/06/2015 21.46.36.362	-0.0145079	229.025	211.975	204.548	225.795	220.544	237.048	275.975	1.92308
30/06/2015 21.46.36.412	-0.0144627	229.079	211.997	204.548	225.741	220.549	237.249	275.985	1.9229
30/06/2015 21.46.36.462	-0.0144196	229.041	211.972	204.548	225.755	220.546	237.279	275.971	1.9229
30/06/2015 21.46.36.512	-0.0144747	229.043	212.003	204.58	225.747	220.505	237.147	275.949	1.92303
30/06/2015 21.46.36.562	-0.0145252	229.004	211.98	204.575	225.729	220.544	237.185	275.969	1.92294
30/06/2015 21.46.36.612	-0.0144756	229.028	211.984	204.55	225.765	220.5	237.066	275.989	1.92295
30/06/2015 21.46.36.662	-0.0144493	229.055	212.016	204.558	225.752	220.551	237.064	275.985	1.92291
30/06/2015 21.46.36.712	-0.0144289	229.033	212.006	204.576	225.753	220.552	237.223	275.955	1.92285
30/06/2015 21.46.36.762	-0.0145136	229.048	212.002	204.543	225.752	220.551	237.124	276.039	1.92298
30/06/2015 21.46.36.812	-0.0145088	228.978	212.023	204.544	225.735	220.481	237.179	275.974	1.92293
30/06/2015 21.46.36.862	-0.0144611	229.012	211.991	204.565	225.764	220.546	237.251	275.993	1.92276

Figure 8 - Example of output table

Note that while the measurements of the incident wave conditions, the internal free surface oscillations and the internal pressure drop are reported in the file mentioned in Table 4 the measurements of the discharge flowing in the outflow pipe positioned in the rear of the models are reported in Table 5.

Table 5 – Measurements of the discharge flowing in the outflow pipe

CONFIGURATION	WAVE	FLOW [l]
PWC_1	H01	0,000
	H02	0,005
	H03	0,010
	H04	0,000
	H05	0,490
	H06	0,025
	H07	1,875
PWC_3	H01	0,000
	H02	0,005
	H03	0,015
	H04	0,000
	H05	0,430
	H06	0,045
	H07	1,390
PWC_4	H01	0,000
	H02	0,000
	H03	0,000
	H04	0,000
	H05	0,000
	H06	0,000
	H07	0,000
PWC_5	H01	0,000
	H02	0,000
	H03	0,020
	H04	0,000
	H05	0,900
	H06	0,100
	H07	2,925
PWC_6	H01	0,100
	H02	0,345
	H03	0,595
	H04	0,000
	H05	1,730
	H06	0,900
	H07	4,450

2.7 Tests

2.7.1 Test Plan

The preliminary Test program is given here below in Table 6.

Table 6 – Preliminary test program (proposal phase)

No.	Test	Runs	Working Days
1	Installation of the model in the flume, check test of the set-up	-	1
2	Free concept test (1) of the POWC (varying water depth & freeboard, check-valve properties). Adjustment model parameters	12	1
4	Case 1 POWC: Measurements (pressure, hydraulic head/water level); Regular wave tests	18	2
5	Case 1 POWC: Measurements (pressure, hydraulic head/water level); Irregular wave tests	12	2
3	Free concept test (Case 2) of the AOWC (varying water depth & freeboard, check-valve properties). Adjustment model parameters.	18	1
7	Case 2 AOWC: Measurements (pressure, hydraulic head/water level); Regular wave tests	18	2
8	Case 2 AOWC: Measurements (pressure, hydraulic head/water level); Irregular wave tests	12	2
10	Dismantling, demobilization	-	1
	Total		12

Detailed description of conducted tests is given here above in section 2.6.

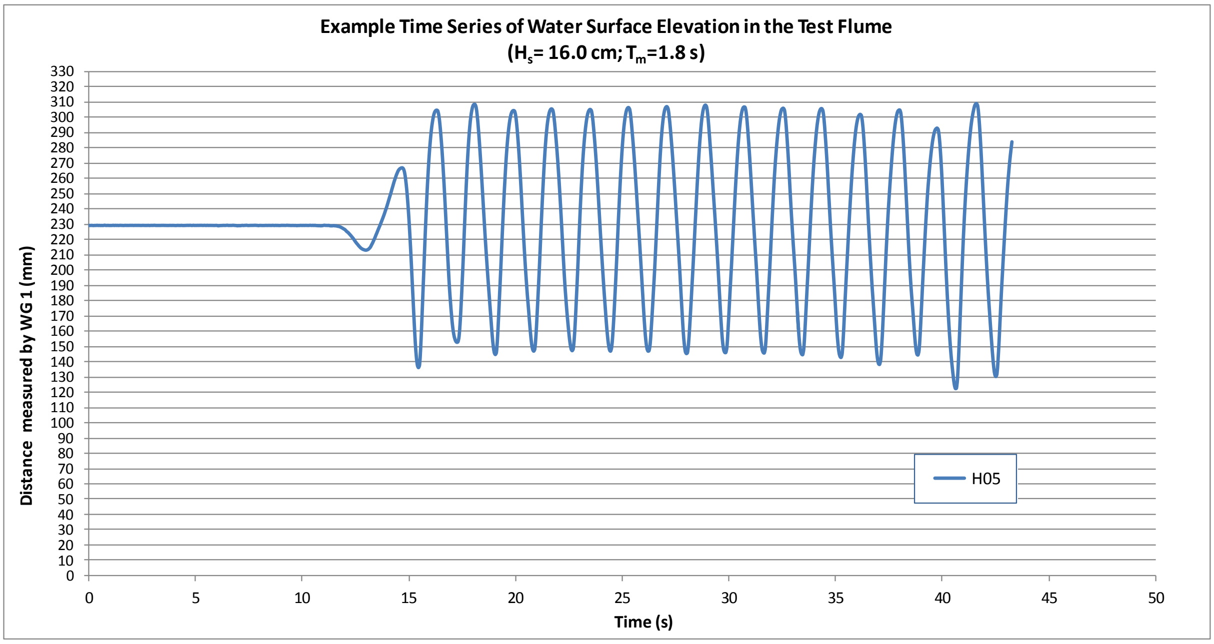
2.8 Results

78 test runs have been carried out, over two basic models on the suggested ‘pressurized’ and ‘alternative’ OWC, under regular and irregular waves.

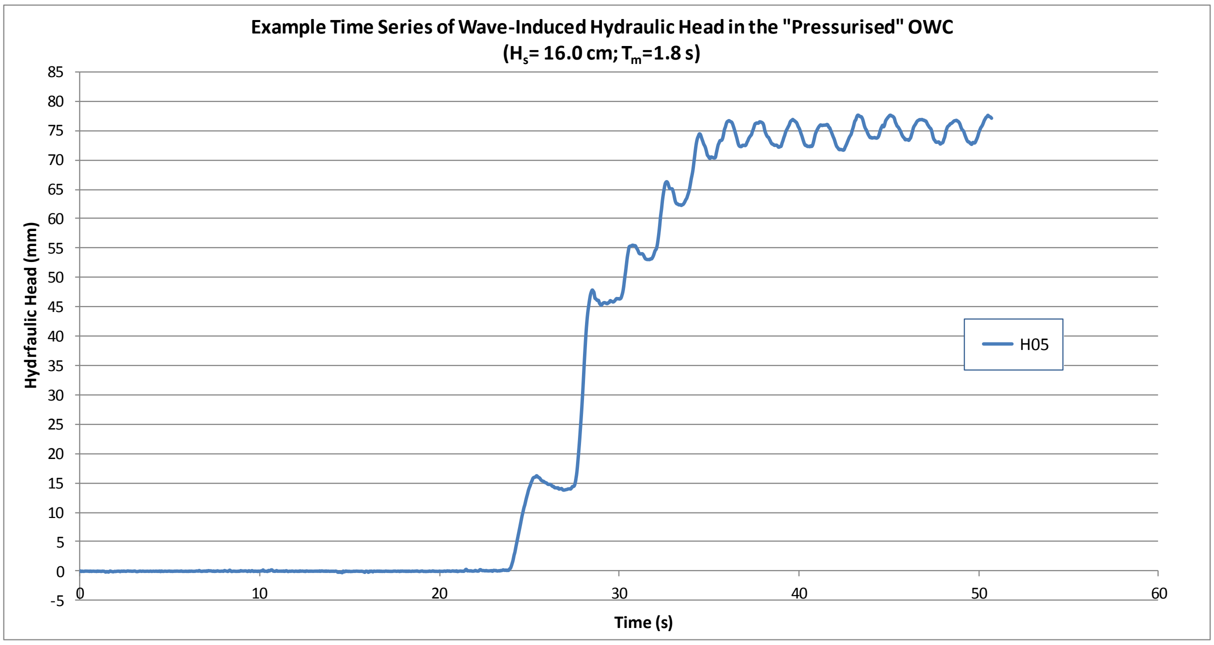
Data will be processes, and results will be published within 6 months after completion of the tests.

Some preliminary results are illustrated here below.

H_s- Significant wave height (incident), (m)
T_m - mean wave period (s)
h_0 - water depth (m)
h_h - hydraulic head (m)

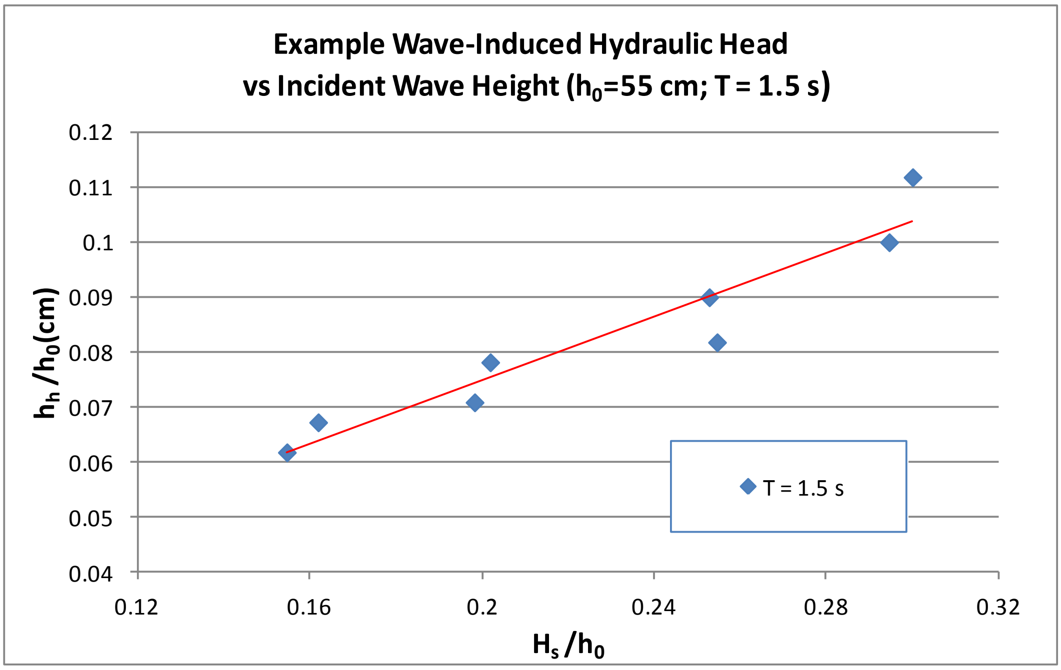


a)

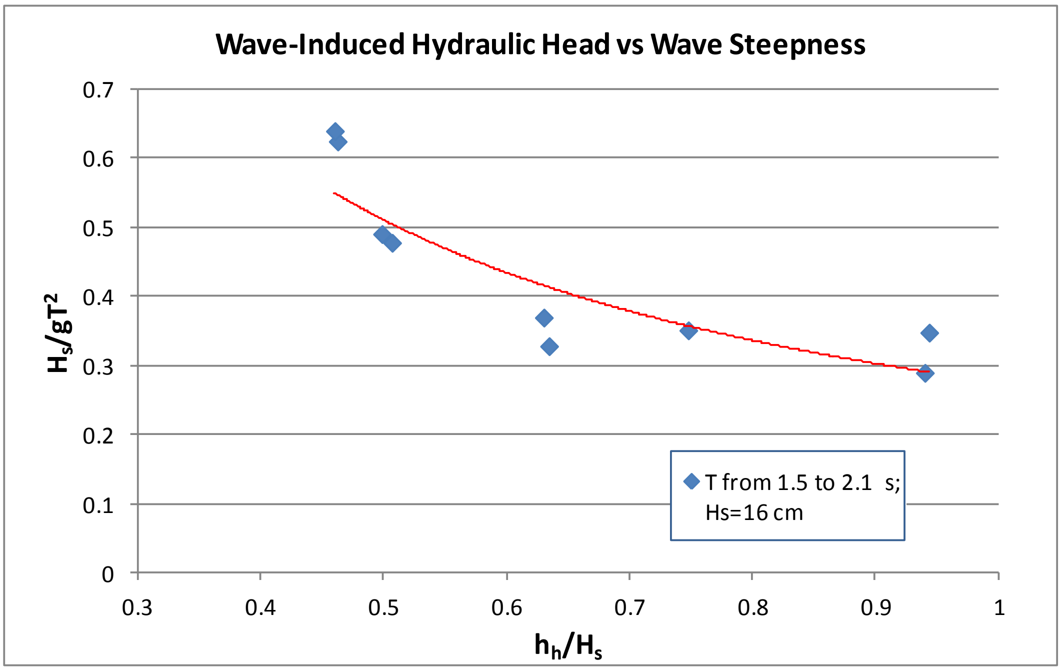


b)

Figure 9 - Example Time Series:
(a) Water Surface Elevation in the Test Flume; (b) Wave Induced Hydraulic Head into the Pressurised OWC



a)



b)

Figure 10 - Examples on preliminary (indicative) test results on Wave Induced Hydraulic Head:
a) as a function of incident wave height; b) as function of wave steepness

All test results will be processed and analysed within a 6 month period after the completion of test.

Some indicative results at this point show that:

- Wave induced hydraulic head inside the "pressurised" OWC is proportional to incident wave height, and for the given range of tested regular waves, it varies as from 0.30 to 0.63 of wave height (H_s). Similar values are detected during a quick check of the irregular wave tests
- Increasing the wave length (decreasing the wave steepness) leads to essential increase of the generated hydraulic head
- It can be expected that a further optimisation of geometry and other components will provide conditions to get even better results in generating a higher hydraulic head.

2.9 Analysis & Conclusions

3 MAIN LEARNING OUTCOMES

3.1 Progress Made

In general, all the tests have been completed according to the plan. During the testing period some new ideas were born, to modify geometry and test-set -up components (pipes, valves, etc), following the observations and current test results. Therefore some extra tests have been carried out, to provide more comprehensive impressions on the tested structure.

As a general conclusion it can be stated that a very good progress was made, in light of clarifying the concept of the “pressurised” oscillating water column. Sufficient data from measurements have been collected, that will give opportunity for further process and analysis, as well as for development of a numerical (CFD) model. Due to restricted time of access (only 2 weeks!) there are still a number of open issues, that need further investigation, in particular concerning possibilities for practical use of the generated hydraulic head for producing electricity.

Some issues can be mentioned, that can be avoided by others in future etc.

- The suggested POWC has shown very good performance in order to generate hydraulic head, however it has been concluded that it hard to be used in practice, unless a complicate valve system is used to regulated pressure differences, and avoid air flow back to the chamber;
- If studies on this (or similar) system are planned in future, it is strongly recommended:
    A. to use mathematical model in advance in order to optimise geometry, in function of wave climate (pressure variations).
    B. To test in advance, and provide high precision reliable valve system, in order to avoid any uncertainties of test results due to imperfections of this component.

3.1.1.1 Next Steps for Research or Staged Development Plan – Exit/Change & Retest/Proceed?

2nd styage of testing can be suggested, in order to take in account ‘*lessons learned*’ and try to optimise parameters, in order to proof (or reject) its applicability.

In that case, some results from numerical modelling (optimisation) could be available by that time, that will give opportunity to build a better model.

3.1.2 Progress Made: For Marine Renewable Energy Industry

The system tested is still at concept level. At this point there is not too much to advice for practical use in Marine Renewable Energy Industry

3.2 Key Lessons Learned

- Suggested POWC has shown very good performance in order to generate hydraulic head, however it has been concluded that it is hard to be used in practice, unless a complicate valve system is used to regulated pressure differences, and avoid air flow back to the chamber;
- The tested alternative AOWC suggests a good way to store the extra energy (released by the check-valve at very high pressure in a conventional OWC) by pumping water in a fee water surface volume. However, more studied are needed to proof this concept and optimise the system.
- If further studies are envisaged in future on these (or similar) system, it is strongly recommended:

– to use mathematical model in advance in order to optimise geometry, in function of wave climate (pressure variations).

– to test in advance, and provide high precision reliable valve system, in order to avoid any uncertainties of test results due to imperfections of this component.

4 ER INFORMATION

4.1 SCIENTIFIC PUBLICATIONS

List of any scientific publications made (already or planned) as a result of this work:

- A publication is planned, title and content to be agreed by partners.

4.2 WEBSITE & SOCIAL MEDIA

Website: under development/upload at www.coresbg.eu

YouTube Link(s): under development/upload

LinkedIn/Twitter/Facebook Links: n.a.

Online Photographs Link: under development/upload at www.coresbg.eu

5 REFERENCES

Testing of a Conceptual Pressurised Oscillating Water Column as a Wave Energy Converter, Project Proposal, V. Penchev et al., MARINET, February 2015

6 APPENDICES

6.1 STAGE DEVELOPMENT SUMMARY TABLE

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.

It is considered that current development is at Stage 1, TRL 1 (with partly components of TRL 2)

DEVELOPMENT PROTOCOL	STAGE 1 CONCEPT VALIDATION			STAGE 2 DESIGN VALIDATION	STAGE 3 SYSTEMS VALIDATION		STAGE 4 DEVICE VALIDATION		STAGE 5 ECONOMICS VALIDATION
	TRL 1: Confirmation of Operation	**TRL 2: Performance Convergence**	**TRL 3: Device Optimisation**	**TRL 4: Sub-Systems Assessment**	**TRL5: Sub-Assembly Bench Tests**	**TRL 6: Full System Sea Trials**	**TRL 7: Solo, Sheltered, Grid Emulator**	**TRL 8: Solo, Exposed, Grid Connected**	**TRL 9: Multi-device Array (3-5)**
Objectives/ Investigations	Op. Verification Design Variables Physical Process Validate/Calibrate Maths Model Damping Effect Signal Phase	Real Generic Seas Design variables Damping PTO Natural Periods Power Absorption Wave to Devise Response Phase	Hull Geometry Components Configurations Power Take-Off Characteristics Design Eng. (Naval Architects)	Final Design Accurate PTO [Active Control] Mooring system Survival Options Power Production Added mass	PTO Method Options & Control Inst. Power Absorption Electricity Production & Quality	Scale effects of Overall Performance Characteristics Mooring & Anchorage Security Environmental Influences & Factors	Oper & Mains Procedures Electrical Output Quality Grid Supply, Stability & Security PTO Performance at all phases Control Strategy Seaworthiness, Survival & Lifecycle Analysis Device Array Interaction (Stages 1 & 2)		Grid Connection Array Interaction Maintenance Service Schedules Component Life Economics
Output/ Measurement	Vessel Motion Response Amplitude Operators & Stability Pressure / Force, Velocity RAOs with Phase Diagrams Power Conversion Characteristic Time Histories Hull Seaworthiness; Excessive Rotations or Submergence Water Surface Elevation Abeam of Devices			Motion RAOs Phase Diagrams Power v Time Wave Climates @ *head, beam, follow*	PTO Forces & Power Conversion Control Strategies	Incident Wave Field 6 D of F Body Motion & Phase Seaworthiness of Hull & Mooring [Survival Strategies]	Full On-Board Monitoring Kit for Extended Physical Parameters Power Matrix Supply forecasting	Array Interaction Annual Power Prod. Elec. Power Perfm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	$\lambda = 1 : 25 - 100$ ($\therefore \lambda_e = 1 : 5 - 10$)			$\lambda = 1 : 10 - 25$	$\lambda = 1 : 2 - 10$		$\lambda = 1 : 1 - 2$		$\lambda = 1:1$, Full size
Facility	2D Flume or 3D Basin			3D Basin	Power Electronics Lab	Benign Site	Sheltered Full Scale Site	Exposed Full Scale Site	Open Location
Duration – *inc Analysis*	1-3months	1-3months	1 3 months	6 – 12 months	6 – 18 months		12 – 36 months		1 – 5 years
Typical No. Tests	250 - 750	250 - 500	100 - 250	100 - 250	50 - 250		Continuous		Statistical Sample
Budget (€,000)	1 – 5	25-75	25-50	50 - 250	1,000 – 2,500		10,000 – 20,000		2,500 – 7,500
Device	Idealised with Quick Change Options Simulated PTO (0-∞ Damping Range) Std Mooring & Mass Distribution		Distributed Mass Minimal Drag Design Dynamics	Final design (internal view) Mooring Layout	Advanced PTO Simulation Special Materials	Full Fabrication True PTO & Elec Generator	Grid Control Electronics or Emulator Emergency Response Strategies Pre-Production Pre-Commercial		Operational Multi-Device
Excitation / Waves	Monochromatic Linear (10-25Δ*f*) (25-100 waves)	Panchromatic Waves (20min scale) +ve 15 Classical Seaways Spectra Long crested Head Seas		Deployment -Pilot Site Sea Spectra Long, Short Crested Classical Seas Select Mean wave Approach Angle		Extended Test Period to Ensure all Seaways inc.	Full Scatter Diagram for initial Evaluation Continuous Thereafter Time & Frequency Domain Analysis		
Specials	DofF (heave only) 2-Dimentional Solo & Multi Hull	Short Crest Seas Angled Waves As Required	Storm Seas (3hr) Finite Regular As required	Power Take-Off Bench Test PTO & Generator	Device Output Repeatability Survival Forces	Salt Corrosion Marine Growth Permissions	Grid Emulator Quick Release Cable Service Ops	Stakeholder Consult. Health & Safety Issues	Small Array (Up-grade to Generating Station)?
Maths Methods (Computer)	Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion		Finite Waves Applied Damping Multi Freq Inputs	Time Domain Response Model & Control Strategy Naval Architects Design Codes for Hull, Mooring & Anchorage System. Economic & Business Plan			Economic Model Electrical Stab. Array Interaction	Grid Simulation Wave forecasting	Array Interaction Market Projection for Devise Sales
	EVALUATION [Stage Gates]								
Absorbed Power [kW]									
Converted Power [kW]									
Weight, [tonnes]									
Manufacturing Cost [€]									
Capture [kW/tonne] or [kW/m^3]	[200-50 m^3]								
Production [c/kW]	< 25 €c / kW			≤ 15 €c / kW			≤ 10 €c / kW		≤ 5 €c / kW

6.2 Any Other Appendices

Attachment 1: Photos from the tests.