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Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	*Closed Cycle Power Take Off for OWC Wave Energy Devices*
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	Name	**Organisation**
Project Partner(s)	William DICK	Waveram (previously named SGL)
Collaborators		

Project Summary (max 500 words)

Wave power has long been an attractive potential source of renewable energy. Wave power has: the highest energy density among renewable energy sources; high availability; good predictability; and is decorrelated with wind and solar power. This is true in many locations in the world, not just Ireland, so this represents a global market for commercialization. However, wave energy is still in infancy, with a large number of concepts at various stages of development. One class of device is called the oscillating water column (OWC) in which the wave power is transferred to air flow. Two problems have dogged the development: the air flow through the turbine is bidirectional and the turbine experiences a large variation in peak pressures in irregular seas. The Closed Cycle Power Take-Off (CCPTO) is a novel concept that addresses both these problems. This project focused on exploring the likely performance of a CCPTO with realistic turbine and valve characteristics. This has been achieved by first determining appropriate sizes for the three air chambers, the valves to yield the operating conditions experienced by the turbine. These data were then used to produce a detailed aerodynamic design for the turbine and hence quantify the turbine power output and efficiency. Using the high fidelity turbine simulations, the overall performance of the CCPTO was investigated for a range of sea conditions. It has been shown that venting the air in the CCPTO and the inertial tanks dramatically improves survivability. For a fixed (shore-based) installation the effect of tide on the power output must also be considered as this changes the maximum compression in the sea chamber.

Keywords (min 3 and max 10)	Closed-Cycle PTO; Wave Energy Conversion; Oscillating water column

NB – Both Section 1 and Section 2 of this Final Report will be made publicly available in a Final Technical Report uploaded online to the National Energy Research Database.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

The RDD/495 award is an early stage applied research project focussing on the assessment and development of the closed-cycle power take off (CCPTO) for oscillating water column (OWC) type wave energy devices. This type of power take off had been proposed in the open literature, and although promising, the previous investigations were limited to gross behaviour of the system under production operational conditions, with key components idealized. This project broadly had two objectives: to identify an appropriate turbine design and investigate the system's behaviour in extreme sea states.These goals were achieved across four technical workpackages and twelve deliverables during the 30 month project. The technical investigations depended on detailed simulations of air flow through the turbine and system level simulations using reduced order models of the behaviour of the CCPTO under different sea states. The turbine design obtained delivered a predicted peak performance approximately 20% higher than the comparable biradial turbine (i.e. with fixed guide vanes) as published in the open literature. It has been found that this turbine if installed as part of a CCPTO in an existing fixed (i.e. shore-based) OWC installation would yield a power output comparable to that obtained with the existing Wells turbine. This is without modifying the sea chamber. Opportunities to significantly improve this performance by tuning the sea chamber volume to the CCPTO have been identified. For a floating installation, it has been found that while venting the air in the sea chamber of the CCPTO during extreme sea states is a viable survival mode, venting the inertial water tanks further reduces the oscillation amplitude. In general, the CCPTO continues to show promise as a configuration to exploit wave energy. However, while many of the subsystems are well understood and have a high Technology Readiness Level (TRL), the system as a whole is still at a TRL of only 2 or 3. To advance to higher TRL will require laboratory testing of some subsystems followed by a scale prototype.

2.2 Introduction to Project

Ocean Waves as a renewable energy source offer a relatively high energy density and limited impact on competing land uses (e.g. agriculture, tourism). Wave power has long been recognized as an attractive potential renewable energy source due to its high density and availability worldwide with early attempts documented in the late 19th century. The ready availability of petroleum suppressed interest in harvested energy sources such as wave power. However, the oil shocks of the 1970s and the growing interest in low-carbon electricity production have resulted in a large variety of concepts at various stages of development. For example, in 2010 it was estimated that there were over 100 active wave energy projectsand it has been reported that there have been over 1000 different prototypes tested. The difficulty in development is caused in part by the variability of the wave energy resource at a wide range of timescales due to individual waves (seconds), weather (days), seasonal variations (months) or even climatic events (years). Nonetheless, the resource has good predictability and is decorrelated with wind and solar power. Furthermore, the potential resource is significant. For example, it has been estimated that the North-Eastern Atlantic potential could be as much as 290GW while the global potential power of ocean waves impinging on coasts is estimated at 1TW.

The first commercial wave energy converter (WEC) was designed by Masuda in Japan in 1965 and consisted of a floating oscillating water column (OWC) device. In an OWC the wave action drives the water in a chamber open to the sea which in turn drives air through a turbine. While work continues on floating OWC devices for both small scale and large scale, there have been several examples of fixed OWCs either shore-based (e.g. Pico, LIMPET) or bottom standing in shallow water near shore (e.g. OSPREY, Oceanlinx). The Pico plant was a 400kW OWC with a Wells turbine commissioned in 1999 in the Azores, Portugal. A similar 500kW device, called the LIMPET was installed in Islay, Scotland. The OSPREY in Scotland and the Oceanlinx in Australia were both large scale near shore, bottom standing OWC devices, but both were destroyed shortly after deployment. However, a comparable device was successfully deployed near Jeju Island, Korea and interest in near shore installations of OWC devices is continuing. Wave energy conversion based on OWC devices whether floating or fixed offers several advantages: the mechanism is not submerged; the sea chamber can provide an effective gearing of the flow; and perhaps the most useful is that the energy presented to the turbine (i.e., in the air) can be dramatically reduced by venting in highly energetic sea states. The main disadvantage is that the flow of air across the turbine is bidirectional i.e., the airflow reverses twice per wave cycle. This has been overcome to some extent with self-rectifying turbines (e.g. Wells, axial impulse or biradial turbines), but these can have poor performance as the rotational speed of the turbine is nearly always mismatched to the instantaneous airflow velocity.

A closed cycle power take-off (CCPTO) system consisting of two large air reservoirs connected by a unidirectional turbine has been proposed and this arrangement was examined for a floating installation. In those studies, the turbine performance was not considered directly.

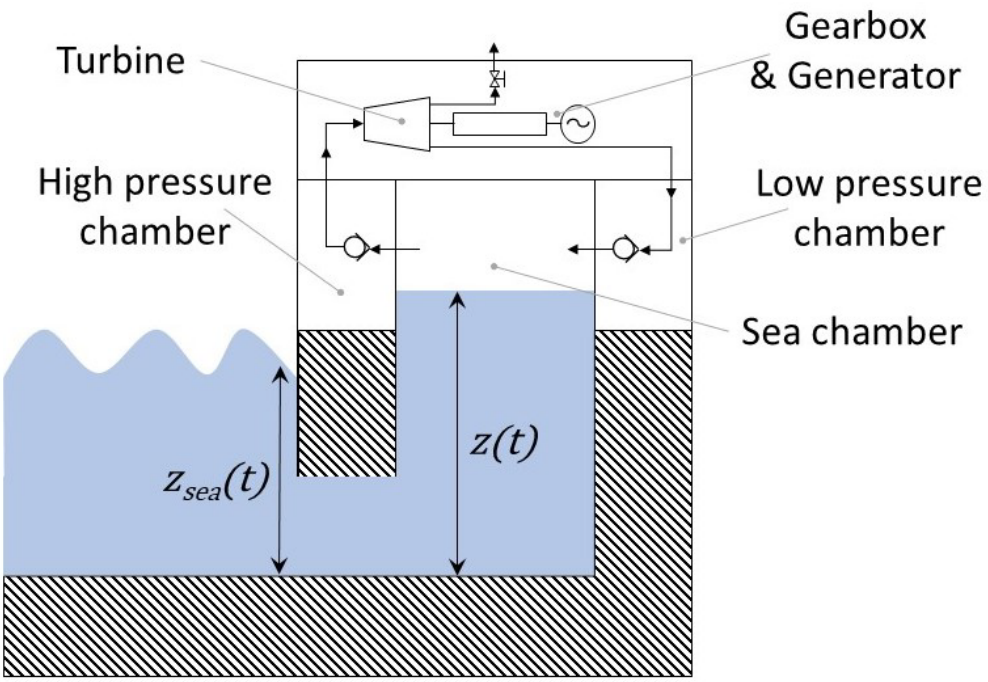

Figure 1 Closed cycle power take-off (CCPTO) for a shore-based installation. Pneumatic path including non-return valves and turbine through the sea, high pressure and low pressure chambers indicated. The PTO will be similar for a floating installtion.

In the CCPTO arrangement, shown conceptually in Figure 1, the power take-off consists of three air chambers: the sea chamber, which is exposed to the OWC, the high pressure (HP) reservoir and the low pressure (LP) reservoir. The sea chamber is connected to the HP and LP reservoirs by non-return valves, while the HP and LP reservoirs are connected by the air turbine. Whether the sea level in the sea chamber of the OWC is rising or falling, the pressure in the HP reservoir is always above that in the LP reservoir, and so the flow across the turbine is unidirectional. This is the principal benefit of this arrangement. An additional benefit is that during excessive sea states, the turbine and generator set can easily be protected simply by venting the pressure chambers.

To understand the operation of the closed cycle PTO, consider the wave cycle as two half-cycles: a compression process and an expansion process. During the compression process, the rising water surface in the sea chamber compresses air raising the pressure, P_S, in this chamber. For a short time, both valves are closed. This is not achieved by active control of the valves but by the temporal variation of the pressure in the three chambers. When the sea chamber pressure rises above the pressure in the HP reservoir, P_H, the HP valve opens while the LP valve remains closed. For the remainder of the compression process, the OWC compresses all the system's air through the HP reservoir, turbine, and LP reservoir. Due to the pressure drop across the valves and turbine, the LP pressure, P_L, is always lower than the HP pressure, P_H. Hence, the LP valve remains closed during the OWC compression process.

During expansion, the opposite happens. The sea level drops in the sea chamber, reducing the pressure, until P_S is below the HP pressure, P_H , which causes the HP valve to shut off. As the pressure P_S continues to drop, it will fall below the LP pressure, P_L, causing the LP valve to open. From this point on, the expansion process is expanding the air in the HP and LP reservoirs into the sea chamber. The compressibility of the air means that the pneumatic spring effect is asymmetric around the equilibrium, with the compression cycle experiencing a harder spring than the expansion. Thus, the system is nonlinear, and it is necessary to model the CCPTO in the time domain.

A key component of the system is the turbine: it is essential to make sure that an efficient turbine can be designed that is suitable for this application. To design the turbine, the specific conditions encountered in the CCPTO are needed. This includes characteristics such as the nominal pressure drop and mass flow rate, as well as their variation.

2.3 Project Objectives

The overall aim of the project was to provide a framework to allow future develop of the CCPTO concept to prototype and beyond. This will address the variation of performance with sizing, turbine characteristics and survival strategy. These engineering goals have been decomposed in to 5 discrete objectives listed in Table 2.1

Table 2.1 – Summary of Project Objectives

No:	**Objective Description:**
1.	Assess the sensitivity of the performance of the CCPTO to gross geometric factors (e.g. accumulator volumes)
2.	Determine the appropriate shape, configuration and performance of the air turbine.
3.	Quantify the effect of blade count and blade sweep on turbine characteristics
4.	Develop appropriate strategies both for survival and enhanced power conversion for CCPTO
5.	Specify the functional requirements for the full-scale air valves.

2.4 Summary of Key Findings/Outcomes

a. **Inclusion of realistic turbine characteristics CCPTO model:** The reduced order model of the CCPTO was previously developed assuming the turbine behaved as a simple orifice. This model has been extended to include realistic turbine characteristics, as so improve the estimate of the WEC performance. This model has been applied to a wide range of sea states and both fixed and floating installations.

b. **Detailed simulation of a reaction turbine targeting the CCPTO operating conditions:** High fidelity CFD simulations of an axial flow reaction for a CCPTO have yielded estimates of the turbine performance which are 20% above designs reported in the literature. It is interesting to note that the turbine can be well represented by an orifice, but the equivalent discharge coefficient depends strongly on the rotational speed of the turbine.

c. **Survival mode:** It has been shown that for a floating installation, venting the CCPTO and inertial tanks will reduce the oscillation amplitude by approximately 50% and hence enhance survival characteristics. Furthermore, it has been found that the peak air pressure is reduced by approximately 35%.

d. **Valve concepts:** Various valve concepts and characteristics have been described and explored in the context of a full PTO system.

e. **Fixed (i.e. shorebased) CCPTO installation**: one of the main lessons learned is that the volume of air in the sea chamber is important in determining the maximum pressurization achievable. Thus, for shore-based installations tide must be considered.

2.5 Project Impact

In 2015, the Expert Group on Future Skills Needs, under the aegis of the Dept of Jobs, Enterprise and Innovation published an assessment of the Skills Needs in the Marine Economy. It was noted that while the ocean energy sector is emerging the main skills requirement would be in technical professionals, including engineers, and that these would be required at Master or Doctoral level (see page 107-108). This project employed two post-doctoral researchers one with background in fluid mechanics the other in turbomachinery. But neither had experience of wave or ocean energy prior to this. In addition an industrial engineer working in wave power was part funded. Thus, the immediate benefit of this project is that three engineers have been exposed to skills that are not specific to Waveram (SGL), but transferrable to the ocean energy sector as a whole. In addition, the publication a journal paper and several conference presentations contributes to Ireland's reputation for academic research in the field of marine energy.

The CCPTO as a concept may solve several of the problems which have dogged the development of commercial wave energy devices for decades: bidirectional flow on the turbine and large variation in peak pressures in irregular seas. Of course, this project did not yield a working commercial prototype, so to promise additional jobs or specific carbon emission reductions would be disingenuous. However, the work that has been delivered in this project establishes a clear framework to plot the trajectory to a commercial offering, which may well contribute to decarbonization and job creation in Ireland. This is consistent with the 2015 White Paper, which states (#139) that ocean energy will play a part in the "medium to long term".

In summary, the impact is threefold:

- Enhanced engineer skills with experience relevant to the ocean energy sector
- High quality research outputs in the open literature
- Progression of the CCPTO concept.

2.6 Recommendations

It is clear that the CCPTO offers a promising path to exploit wave energy. In the medium term, a fixed, shorebased installation could be integrated to new coastal defences of harbour walls, especially on the west coast. A floating installation offers the opportunity to exploit the wave resource offshore off the west coast. As this is still an immature technology, supports in the form of additional research funding, prototype development funding and ultimately price supports for early commercial installations will be necessary.

2.7 Conclusions and Next Steps

Waveram (formerly SGL) continues to develop the concepts and technology associated with the CCPTO. This project, and others, have generated significant understanding of the likely performance of this type of wave energy conversion device in both production and extreme conditions. Furthermore, awareness has been gained of the likely challenges for integrating the various elements and subsystems into a complete solution. Future work in modelling the behaviour of a floating installation would include more degrees of freedom (i.e. include pitch, roll, surge and sway) as well as nonlinear wave effects such as crashing. Some lab testing of subsystems would be useful: any design/fabrication of the turbine could be substantially characterized and validated in a laboratory test cell and the valves could be tested in isolation, although probably not dynamically. However, quite rapidly the step required will be a small scale prototype. The difficulty with achieving dynamic similitude for a small-scale physical model simultaneously for compressibility, viscous effects (in both aero- and hydrodynamics) and relative/apparent velocities in the turbine the means that wave tank testing with a functioning PTO would be of very limited value. Therefore, quite rapidly after the subsystems are designed and tested a small scale (e.g. 1:4 geometric scale) in a testing ground such as Smart Bay in Galway, or Mutriku in Spain.