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AWS Wave Power Development Experience

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Contents

Figures, Tables & Appendices

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Nomenclature & abbreviations

Name or acronym	Explanation
3-D	Three-dimensional
AWS	Archimedes Waveswing
AWS-III	The floating multi-cell wave energy absorber design promoted by AWS Ocean
AWS Ocean	AWS Ocean Energy Ltd
EAP	Electro-active polymer
EMEC	European Marine Energy Centre
FEED	Front end engineering design
FRP	Fibre-reinforced plastic
HMRC Cork	Hydraulics and Maritime Research Centre, Cork
IAMS	Intelligent active mooring system
LCOE	Levelised cost of energy
M & E	Mechanical and electrical
MARIN	Marine Research Institute Netherlands
Pilot plant	The 690kW AWS plant deployed off Portugal in 2004
Proa	The name adopted for the unequal catamaran hull used for the AWS-III design, originating from the name for a Polynesian outrigger canoe
PTO	Power take-off
SDPS	Self-drilled Piling System
S-Wave	An AWS-III diaphragm design with ‘S’ shaped sides
WEC	Wave energy converter
WES	Wave Energy Scotland

1 General

1.1 Introduction

This document has been produced in response to a brief by Wave Energy Scotland (“WES”) to report on the AWS wave power development experience.

The report was produced in August 2015 and reviews the experience of AWS Ocean Energy Ltd from May 2004 to the time of writing. It also references the earlier experiences gained from the work by Teamwork Technology (Netherlands) in the initial development of the Archimedes Waveswing™ in the period from 1994 to 2004.

Much of the report is technical and requires a reasonable level of understanding of wave power principles and technology on the part of the reader. The report does not however provide all of the background technical information, much of which is proprietary intellectual property of AWS Ocean Energy Ltd.

The report is however intended to give an overview of the development experience and the key decisions and to provide a signpost to more detailed technical information so that Wave Energy Scotland may be aware of the existence of our work and therefore avoid repetition and promote future collaboration.

1.2 AWS Ocean Energy Ltd

AWS Ocean Energy Ltd (“AWS Ocean”) was founded in May 2004 in order to commercialise the Archimedes Waveswing™ wave power technology. Since that time, the company has invested some £18 million in research and development of wave energy technology and related systems including:

- The Archimedes Waveswing™ - a sub-sea, pressure-differential point absorber wave energy converter using both linear generator and hydraulic power take-off;
- The Electric Eel™ - a sub-sea, flexible, bulge-wave attenuator wave energy converter using electro-active polymer power take-off;
- The AWS-III (or CLAM) – a floating, multi-absorber terminator wave energy converter using air turbine power-take-off;
- The Self-drilled Pile System – a remote piling technique for provision of anchor points for marine renewable energy devices in high current or high turbulence sites;
- The Intelligent Active Mooring System – a braid-pump based active mooring component designed to reduce the structural and anchor loads in floating marine renewable energy devices.

Accordingly, the company has experience of a range of WEC technologies, including point absorbers, surging terminators and attenuators. In terms of power-take-off, AWS Ocean has experience of

linear generators, hydraulics, air turbines and electro-active polymers, whilst in terms of ancillary systems AWS Ocean has investigated numerous mooring and anchoring configurations and is developing technology for application to a wide range of marine renewable energy devices.
Both the Archimedes Waveswing™ and the AWS-III have been advanced to the stage of detailed design supported by sophisticated numerical modelling, performance testing and component development and testing. This work has been documented by the AWS Ocean team over the years and provides a significant body of knowledge.

AWS Ocean has employed over 100 people during the past 11 years, with the majority of these having been highly educated professionals selected from a number of different industries, including offshore oil & gas, subsea engineering, aerospace, automotive, power generation and heavy engineering.

It is hoped that the considerable body of knowledge built up over the years will contribute to the eventual realization of commercial wave power.

2 Timeline overview

2.1 Timeline introductory narrative

AWS Ocean was founded in 2004 to commercialise the Archimedes Waveswing™ wave power converter technology. The Archimedes Waveswing™ or “AWS” is a sub-sea pressure-differential activated point absorber, invented by Fred Gardner (Netherlands) in 1994. The technology was developed by Gardner’s company Teamwork Technology BV over a period of 10 years, culminating in the deployment of a 2MW (peak) rated ‘pilot plant’ off northern Portugal in 2004. This plant first delivered power to the grid on 3 October 2004 having been delayed for several months due to control system problems. But for this delay, the AWS Pilot Plant would have achieved a world first in delivering offshore wave power to a national electricity grid, this prize having been claimed by Pelamis some 6 weeks earlier.

Following incorporation, AWS Ocean focused on raising investment funding whilst Teamwork Technology continued the technical development of a second-generation AWS. The IP rights in the AWS technology were transferred to AWS Ocean in late 2005 ahead of the first venture capital investment (£2 million by RAB Capital) which completed in April 2006. The investment allowed AWS Ocean to begin to build a technical team and broaden its engagement with commercial partners.

With the increase in rigor and commercial focus brought by the AWS Ocean team, it was soon realised that the original Waveswing™ concept would require significant development to allow it to produce power at an economic cost. This led to several iterations of the Waveswing™ both in terms of the absorber and structural elements and in terms of the power take-off. Significant effort was contributed by industrial partners including Converteam (now part of GE), Bosch Rexroth, Global Maritime, Isleburn and others. This effort was funded through a further £3.5 million investment round led by Shell Technology Ventures (STV) which completed early in 2008.

By mid-2008 the Waveswing™ MK II device was at an advanced stage of engineering with the sub-systems all defined and structural design largely complete. Performance simulation models were developed and survival trials completed at 1:50 scale. Costs for the device – particularly the PTO and essential spring systems – had however escalated whilst performance predictions had been down-graded, resulted in a projected cost of energy of between £500 and £700 per MWh for a first mini-farm of devices. As a result the AWS Ocean Technical Advisory Committee concluded that the current configuration of Waveswing™ was unlikely to reach commercial viability and hence recommended suspension of further development.

There followed a period of intense innovation activity when the team examined a wide range of embodiments of the Waveswing™ concept in order to find a solution which provided the prospect of economic wave power at utility scale. Whilst the Waveswing™ was capable of performance close to an ideal (stroke-limited) point absorber, the costs associated with countering the hydrostatic spring forces were too high. This process led to an evolution of the Waveswing design to something close to the original CLAM design invented by Norman Bellamy of Lanchester Polytechnic in 1983. AWS

Ocean contacted some of the original Lanchester team and carried out a detailed review of the past work from which it was concluded that the CLAM concept could yield an attractive LCOE and that AWS Ocean should pursue this technology stream as an alternative to the Waveswing™. A variant of the CLAM concept was re-branded the AWS-III and technical development work began in March 2009, leading to a further £2.0million investment round by STV and Scottish Enterprise which closed in December 2009.

Early 2010 saw intense focus on development of the AWS-III including the deployment of a 1:10 scale model on Loch Ness in April 2010. The demonstration crystallised the interest of utility customers and this, together with support from the Scottish Enterprise WATERS grant was key in securing further investment which arrived in the form of a £8.0 million staged investment by Alstom which closed in June 2011. Development of the AWS-III continued with various hull forms and diaphragm options being explored during 2011 and 2012. Optimisation was carried out by means of tank tests at Strathclyde and Heriot Watt universities and two significant performance test campaigns were completed at the Maritime Research Institute Netherlands (‘MARIN’) facility in the Netherlands.

Following optimisation, AWS Ocean conducted the FEED for a prototype device with outline design and costing being completed by Damen Shipyards, Alstom and others. The result was an engineered and costed prototype design for which performance was well understood and verified by scale test. Unfortunately market issues (including the withdrawal of utility companies from wave energy and uncertainty surrounding electricity market reform) conspired to undermine the case for further investment in the AWS-III technology and in March 2013, Alstom confirmed that they would not invest further in the company.

The remainder of 2013 was taken up with documentation of the learnings achieved to date and disbanding of the majority of the AWS team which by this time had reached 36 people. This process was completed by December 2013 when management completed a buy-out of the company from the institutional shareholders.

During 2014 and early 2015, focus has been on transforming the company to a sustainable trading entity which can leverage the significant knowledge gained through 20 years of R & D in wave power. In September 2014, the Waveswing™ designs were re-visited and a significant innovation was identified which will allow removal of the high costs associated with the spring elements whilst also allowing down-scaling of the Waveswing™ to meet the current market opportunities. The company is now focused on the re-development of the Waveswing™, building on the body of past work, whilst maximizing the benefits of the recent innovations. This will allow the company to gain valuable market traction and operational experience at smaller scale, and in due course apply the learnings to enable larger scale devices for bulk power production.

2.2 AWS Wave power development – key phases

The AWS Ocean timeline is presented in graphical form in the appendices to this report and includes a number of key phases as follows:

1994 – 2004	Development of the original Archimedes Waveswing™ concept by Teamwork Technology; Tank testing at Technical University of Delft and HMRC Cork; Design, build and deployment of 2MW pilot plant off Portugal.
2004 – 2007	Further development of high-volume Waveswing™ towards 1MW pre-commercial prototype.
2007 – 2008	Development of evacuated low-volume Waveswing™ towards 250kW technology demonstrator. Invention of Electric Eel™ and Self-drilled Pile System.
2008 – 2009	Search for economic solution to Waveswing™ and evolution to 'S-Wave' diaphragm based device;
2009 – 2011	Development of 'S-Wave'; Scale model proof of concept on Loch Ness; Evolution to AWS-III non-straining diaphragm device.
2011 – 2013	Intensive development of AWS-III device including full FEED of 2.5MW 'first-of-a-kind' device for EMEC.
2014 – Present	Completion of half-scale single-cell test for AWS-III and development of Waveswing and AWS-III designs for smaller power isolated markets. Development of Intelligent Active Mooring System ("IAMS").

The breaks between phases are punctuated by key decisions which are noted and discussed in section 4 of this report.

3 Brief description of AWS technologies

3.1 Archimedes Waveswing™

The Archimedes Waveswing™ is a submerged heaving point absorber Wave Energy Converter designed for offshore wave energy production. The system is essentially a telescopic canister with an outer moving “Floater” and an inner fixed “Silo”. The floater and Silo are connected by a power take-off (PTO) and a structural leg connects the Silo to a gravity-base anchor via a universal joint. Part of the Floater / Silo chamber is evacuated to give a compressive force to resist the buoyancy of the Floater.

Operation of the WEC is conceptually simple whilst elegant. At mid-stroke the Floater buoyancy balances the vacuum chamber compression. An approaching wave crest increases the external hydrostatic pressure on the Floater causing an imbalance in forces and hence the Floater moves down-wards. This causes compression of the Floater gas which reduces buoyancy, whilst the vacuum chamber volume is decreased, raising the pressure and hence balancing the loss in floater volume. The floater continues to compress until the force equilibrium is re-established, thus achieving a multiplication of the wave height without the need for resonant behaviour. The wave is absorbed due to the void created through contraction of the WEC volume. The process is reversed for a wave trough. The very ‘flat’ spring curve coupled with a light Floater means that device response is not dominated by resonant behaviour and this allows tuning of the device response via the PTO for maximum power conversion.

For shut-down or survival the Floater is de-pressurised and retracts to bottom-dead-centre where the lower lip of the floater seals against a rim around the silo. The device is held fully compressed by the vacuum force. The device pitches about the anchor joint in order to shed load in large waves. Pitch motions in excess of 20 degrees can be expected although much larger motions can be tolerated by the design.

The device is fully scale-able from sub-kW scale to MW scale and follows Froude scaling laws. For example a 3.6m diameter x 4m stroke device would be rated at 40kW whereas an 8m x 8m device would be rated at 450kW. It is intended that the first prototype system deployed in the sea will be rated at 40kW whilst it is expected that pre-commercial demonstration systems will be rated at 100kW.

A schematic of the basic Waveswing™ operation is shown in Figure 1 whilst a conceptual render is presented in Figure 2. A more detailed technology description of the Waveswing is provided in AWS Ocean report for WES, reference 15-007.

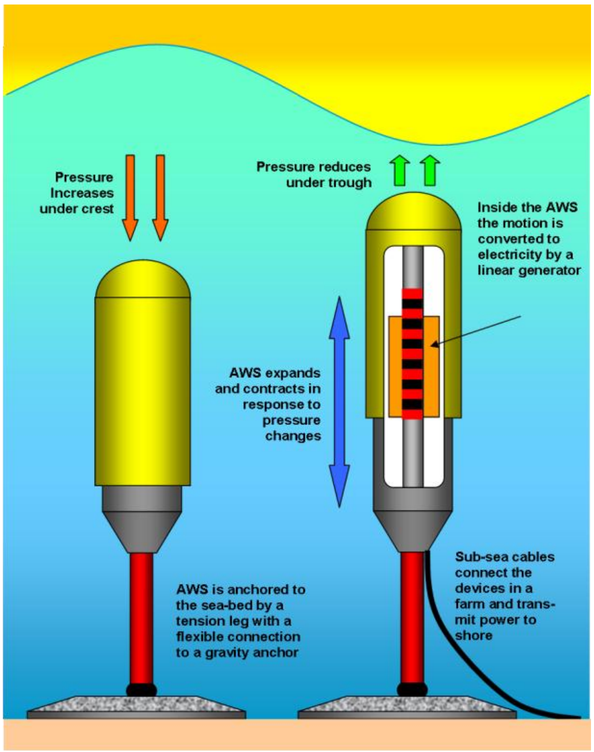

Figure 1: Waveswing schematic

Figure 2: Waveswing concept render

3.2 Electric Eel

The Electric Eel is a submerged pressure differential Wave Energy Converter concept designed for offshore wave energy production. The device is constructed entirely from flexible materials and utilises advanced electro-active polymer artificial muscle (EPAM) as the power take-off mechanism. The device is similar to the Anaconda wave energy device (see www.bulgewave.com) with the key difference being the use of EPAM in the PTO which provides potential improvements to the overall device operation.

The device essentially comprises a submerged water-filled distensible thin-walled tube which is moored close to the surface of the sea and head-on to the waves. A ‘bulge wave’ is generated in the tube by the action of the ocean waves and this bulge wave increases in size as it travels down the tube. The circumferential strain of the thin tube walls caused by the bulge can be converted to electrical energy by the PTO.

The device is fully scale-able from sub-kW scale to MW level. A candidate device of 7m diameter and 155m length was sized at 750 kW. Larger devices have been sized up to a rating of 5.25 MW.

A concept drawing of the Electric Eel is presented in Figure 3 and a more detailed technical description is provided in AWS Ocean report for WES, reference 15-009.

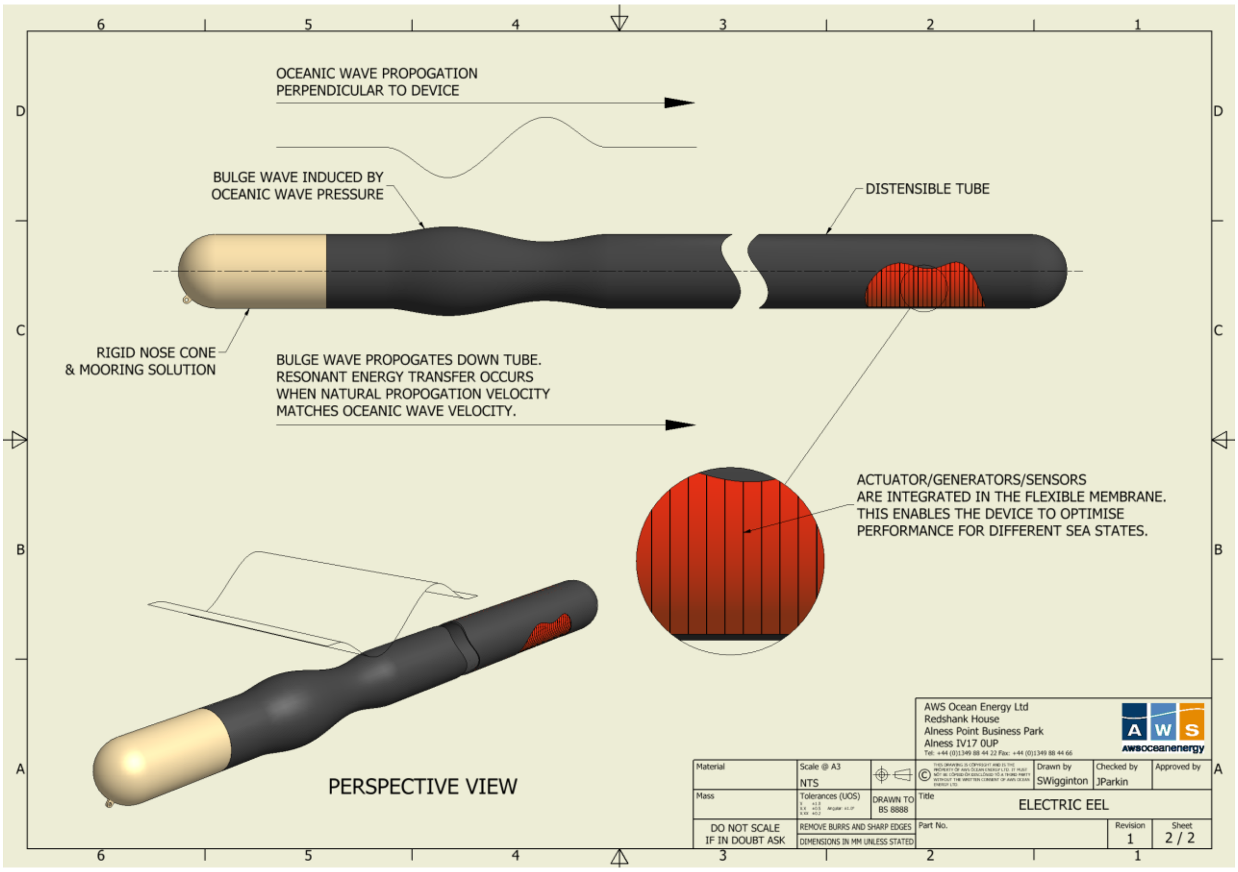

Figure 3: Electric Eel concept drawing

3.3 AWS-III

The AWS-III is a multi-absorber floating WEC which uses rubber diaphragms which cover air-filled cells as the primary power absorption mechanism. The devices are physically large – typically 120m by 45m for a 8 cell device rated at 2.0MW. All mechanical moving parts are isolated from the sea and contained within the device, whilst the power take-off is by means of tried-and-tested air turbine technology as developed by Voith, Dresser-Rand and others. The device is moored using traditional catenary systems and drag-embedment anchors.

Each cell is partially submerged and with the internal air pressurised such that the face of the diaphragm sits at the mid-point of its range of motion under still-water conditions. The diaphragms are a 3-dimensional shape so that they are capable of deforming both inward and outward according to the pressure balance between the external hydrostatic pressure and the internal pneumatic pressure. The face of the diaphragm tends to remain largely vertical as it moves through the range of motion and thus each cell operates much like a piston wave-maker, but in reverse (i.e. absorbing waves rather than generating them). If the cell PTO damping is correctly arranged to match the hydrodynamic damping, full absorption of an incident wave is possible.

The technology can be configured on a range of hull shapes with the number of cells selected to suit conditions. The most advanced form of the AWS-III design uses a twin-hull 'Proa' design as shown in Figure 4. The diaphragm wave absorbers are anticipated to require regular replacement and hence are mounted on a cassette which allows rapid removal and replacement at sea, whilst also facilitating full assembly, sealing and testing of the unit in factory conditions ashore.

The device is scale-able from kW scale to MW scale and follows Froude scaling laws. For example a nominal full-scale device comprising 8 power generating cells, each 16m wide by 8m high be rated at 2.0MW (250kW per cell) whereas a 1:4 scale device incorporated into a fish cage would have a rating of 15.6kW. The device is intended for larger-scale utility power production, however lower-cost options for remote applications where the technology can be integrated with existing structures is also under consideration.

An image of the most recent design for the AWS-III is shown in Figure 4 and a more detailed technology description is provided in AWS Ocean report for WES, reference 15-008.

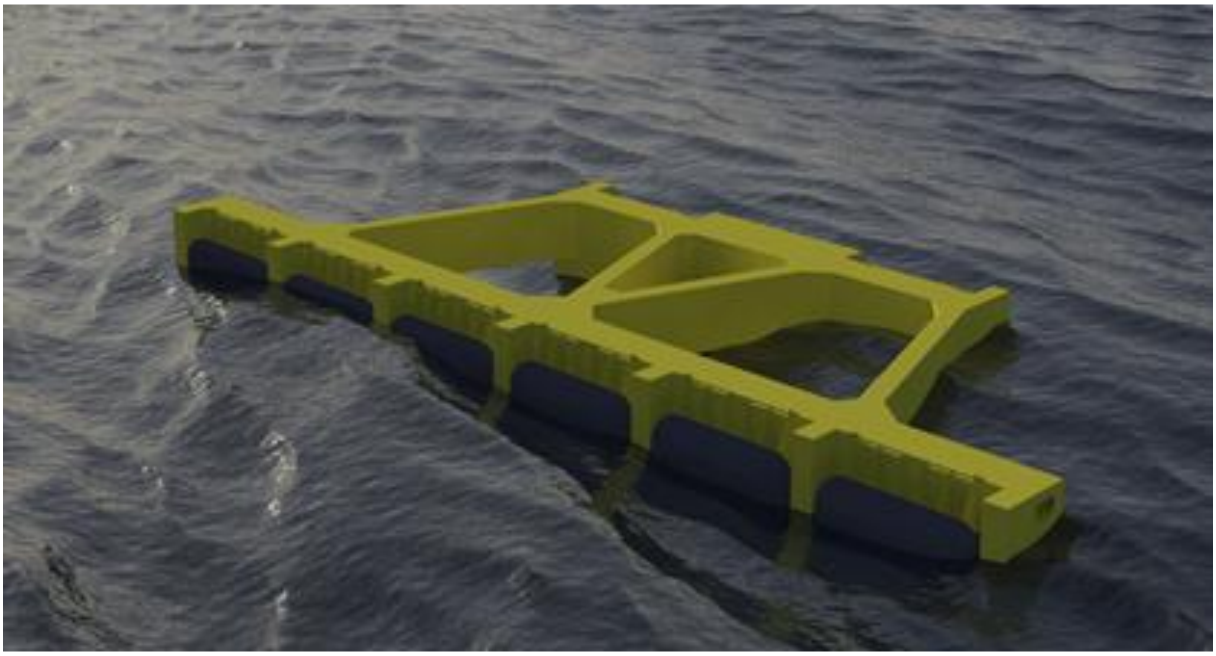

Figure 4: AWS-III Proa design

3.4 Self-drilled Pile System

The Self Drilled Pile System (SDPS) provides a means of installing a subsea piled anchor through the use of a drilling rig remote from its support vessel connected only by an umbilical. By removing the fixed vessel-drill link a wider weather window may be used along with a more readily available (and consequently cheaper) vessel. The concept was conceived to solve a mooring/anchoring problem which was identified during development of the Waveswing™ Mk II device. Devices such as this which encounter uplift (vertically loading the anchor) were, with existing technology, forced to use either very large gravity anchors or a piled system requiring a large jack up vessel. Both these methods can involve large, expensive vessels with limited availability.

The SDPS comprises a number of sub systems, many of which are already in use in the offshore sector. The key novelty is in the use of telescopic piles inserted through a base frame. This means that each pile can be shorter and hence avoids overturning loads due to high currents, and is lighter to handle.

Details of the key components are shown in Figures 5, 6 and 7 and a more detailed technical description is given in AWS Ocean report for WES, reference 15-010.

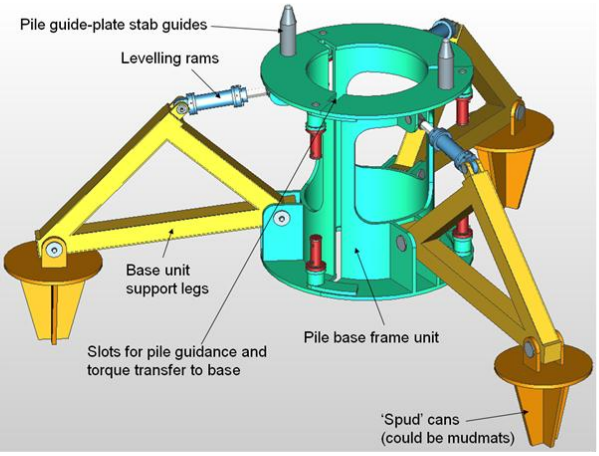

Figure 5: SDPS base unit

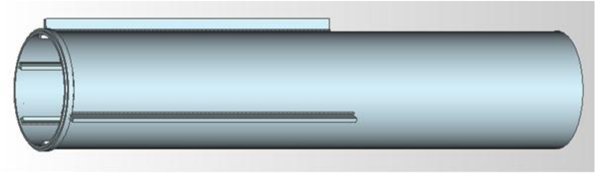

Figure 6: SDPS finned pile

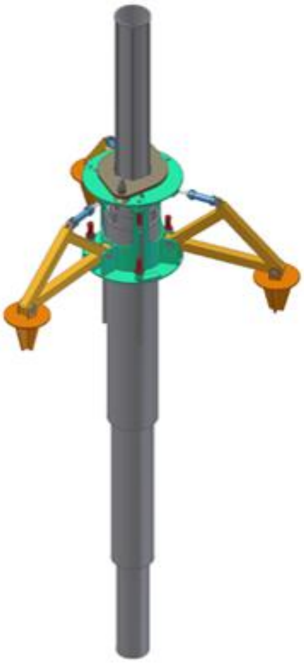

Figure 7: Complete SDPS assembly

4 Key results

AWS Ocean has researched a range of wave power absorption methods and worked with industrial partners to develop conversion systems based on all of the major PTO technologies. As a result we are able to draw a number of conclusions in relation to wave power in general and some conclusions regarding specific technologies or issues. It is interesting to note that some issues recur across seemingly widely different technology platforms.

An important piece of work for the future will be the cross-validation of various conclusions, and further research into the underlying reasons for common issues. The results that we have observed are as follows:

4.1 Waveswing results

4.1.1 1:50 scale tank testing, HMRC Cork, 1998

A series of tank tests were undertaken at HMRC, Cork in 1998 with the key results being:

- The use of linear wave theory for prediction of the behaviours of the Waveswing™ was shown to be valid;
- Measured hydrodynamic damping and diffraction forces accorded well with the predicted results;
- Measured added mass was significantly higher than predicted (1.5 to 2 times higher);
- Efficiencies varied from 40% to 100% depending on sea-state and model set-up;

These results were used to inform the design of the AWS MK 1 pilot plant.

4.1.2 Numerical modelling

Various numerical modelling techniques have been used over the years to predict the behaviour and energy yield of the Archimedes Waveswing. Key results are as follows:

- Models tend to converge in terms of performance predictions with significantly different approaches yielding similar results;
- A fully developed time-domain model of the Waveswing MK II was developed to include all degrees of freedom. This model could be adapted to other point-absorber technologies;
- The use of a fully-coupled time-domain simulation provides valuable insights into device survivability – for example predicting pitch motions and anchor loads under extreme wave conditions;

The numerical models have recently been updated to run on the latest versions of Matlab and Simulink.

4.1.3 AWS MK 1 Pilot Plant, Portugal, 2004

A large-scale AWS 'Pilot Plant' was constructed to provide proof-of-concept of the AWS. Detailed design and construction was commenced in 1999 and the structure was first launched in 2000. Key outcomes were:

- The operation of the AWS technology was demonstrated at large scale, providing power to the Portuguese grid in October 2004, narrowly missing a world-first for delivery of offshore wave-power to a grid – Pelamis having achieved this some 6 weeks earlier;
- Construction of a large prototype can be controlled well, however the marine deployment of such a device can give rise to significant and unforeseen problems such as stability during submergence;
- Deployment issues were resolved and the final deployment was well controlled and successful;
- Quality control in the commissioning procedures was lacking, resulting in a critical error – namely that the controls pod was not sealed and charged with nitrogen. This resulted in total loss of control to the test device and almost compromised the whole project;
- Foresight in the design provided for remote intervention means and accordingly, the device could be operated from the surface and this allowed test results to be obtained;
- Overall, the project provided very significant experience for the team, however the perceived failure caused by the controls system issues caused negative PR;
- For future projects, a less ambitious approach is recommended;

The plant was decommissioned in December 2004 although the sub-sea cable, shore-station and grid infrastructure remained in place and was subsequently used by Pelamis.

4.1.4 Development of Waveswing™ MK II designs

The development of the Waveswing™ MK II designs took place over a period from December 2004 to September 2008. During this period numerous configurations of the basic AWS design were considered. The following outcomes are considered key:

- A large (i.e. MW) scale Waveswing™ using only a soft air spring was not economically feasible (given known technology at the time), although a technically feasible solution was found using concrete construction;
- A low-volume Waveswing™ using only a single evacuated chamber and high-pressure hydraulics is unlikely to be economically viable due to the high costs associated with the complex mechanical systems and the inherent reliability issues with such a system;
- Notwithstanding the economic issues, detailed design work showed that the evacuated design was technically feasible at a rating of 250kW;

- The evacuated Waveswing™ design had a sector-leading power to weight ratio and but for the cost of the mechanical systems, was considered by external reviewers to represent the leading prospect for lower cost wave energy at the time;

Work on design development of the Waveswing MK II was suspended in August 2008 and the decision to cease development for the foreseeable future was finally taken in February 2009.

4.1.5 Parametric modelling & optimisation

During the course of the development of the Waveswing MK II designs, it became clear that finding an economic solution was not a trivial task. The AWS Ocean team therefore adopted a parametric modelling approach in an attempt to understand the key drivers behind the economics of the Waveswing™. It was hoped that this knowledge would assist with finding an economic solution to the design challenge, or alternatively confirming that no economic solution was possible and hence another technology should be investigated. Key results and outcomes are as follows:

- Parametric modelling provides an invaluable tool for optimisation of wave energy converters, highlighting areas for investigation likely to give best results;
- Device cost tends to increase approximately linearly with displaced volume;
- Energy yield per unit volume decreases as displaced volume increases. This is because small volume absorbers tend to be exercised at full capacity by relatively smaller waves, whereas larger absorbers require larger waves and hence are utilised fully for a lower percentage of time;
- A result of the previous two points is that it is unlikely that point-absorber technology can achieve effective economic performance at large (i.e. MW) scales. Best results are obtained from smaller devices;
- Site location and survival conditions are a key cost driver. Better economic performance may be achieved from lower energy sites with more even wave resource spread throughout the year;

The modelling work was curtailed after initial results were obtained and indeed only focussed on the Waveswing™ as this was the only technology of interest at the time. Further development of this work could be of value to the sector, both in terms of generic modelling tools and in terms of tools tailored to specific technology families.

4.2 AWS-III results

4.2.1 Initial diligence and evaluation, 2009

This exercise was undertaken in order to underpin a decision to invest significant funds in the development of the AWS-III technology. Key results are summarised as follows:

- The S-Wave variant of the Coventry CLAM designs appeared to present an attractive opportunity for the development of utility-scale wave power with LCOE below 15 pence/kWh in a 44kW/m resource;
- The key sensitivities to achieving a low LCOE were accessing high wave energy resources, improved capture and conversion efficiency, reduction in hull fabrication costs, reducing M & E plant costs, achieving sufficient diaphragm life and reducing mooring and deployment costs;
- The technology was assessed as being competitive with deep-water offshore wind with lower risks and higher power density per km^2 of sea-bed;
- The analysis recognised the technical uncertainties and in particular highlighted the challenge of up-scaling to a 90m diameter (20 cells at 16m wide by 8m high) device

This was the first time that AWS Ocean had used a Monte Carlo simulation to consider the risks and probabilities underpinning the LCOE assessment. Note that the methodology is further detailed in AWS Ocean report for WES, reference 15-011.

4.2.2 Loch Ness 1:10 Scale testing, 2010

This project was undertaken in order to provide a rapid and cheap proof-of-concept test of the S-Wave technology using the local resources available to the company. Key results are summarised as follows:

- A power matrix was produced which indicated that the S-Wave variant of the Clam captured wave power as effectively as the previous Coventry CLAM designs in the Loch Ness resource;
- The 12 cell dodecagon shaped device was prone to dynamic instability due to the changes to free-surface area as the diaphragms inflated and deflated;
- Survivability during storms (Hs 8m full-scale equivalent) was demonstrated;
- The S-shaped diaphragms were prone to fatigue failure in the ‘stretch’ zones either side of the central (non-stretching) portion of the diaphragm;
- The AWS Ocean team was able to design, build and deploy a model at reasonable (6m diameter) scale in a short period. This process provided significant learnings for the team and informed many of the aspects of future model design for more expensive wave-basin tests;
- The results of tests in an uncontrolled resource are difficult to analyse due to the fact that the input resource can only be measured in terms of sea-state parameters and not on a wave-by-wave basis;
- The tests were an excellent proof of concept and key to securing customer engagement and buy-in to the technology;

Overall, this project served to underline the importance of early physical testing of any WEC concept and proved that this can be done at reasonable cost. The moorings remain in place and could be used for future open-water device testing if required.

4.2.3 MARIN 1:15 scale testing of Dodecagon, 2011

This project was initiated in order to obtain high-fidelity performance data for the AWS-III with a 3-D diaphragm configuration, to investigate the effects of various device parameters on power performance and to provide data for validation of numerical modelling. Key results are summarised as follows:

- The team achieved 299 separate wave test runs over a period of 10 tank-days, demonstrating the benefits of rigorous preparation and pre-commissioning ahead of the test period;
- The power matrix was recorded and showed a 23% improvement over the baseline for economic assessment of the AWS-III as agreed by the AWS Ocean board;
- A power matrix was produced which allowed prediction of the device pneumatic performance for any given sea-state;
- Under-performance of some cells resulted in the device failing to achieve the target power rating of 2.5 MW (electrical), equivalent to around 5 MW pneumatic;
- The optimised pneumatic damping was found to match available Wells turbine designs;
- Displacement (i.e. draft) and operating pressure have a strong influence on power capture;
- The dynamic instability or 'bubble' effect was still in evidence and appeared to detract from power capture;
- The tests were only conducted in long-crested seas. Due to cell interactions it was expected that short-crested seas might yield higher performance;

Further to the above, the team collected valuable data on mooring loads, device RAOs and diaphragm response characteristics.

4.2.4 Hull shape optimisation, 1:30 scale, Heriot Watt, 2012

This project was initiated following the MARIN tests of the 12-cell dodecagon in order to investigate ways of improving performance through varying the hull plan-form. It was anticipated that better balancing individual cells and improved vessel stability could be achieved which could result in overall performance gains. Key results are summarised as follows:

- An overall average increase in energy capture of up to 25% over the 12-cell dodecagon may be possible with some hull shape variants in a typical Scottish Atlantic resource;
- Device heading relative to incoming waves is important for some hull shapes, with up to 30% improvement from head-seas possible;
- A catamaran operating beam-on to the seas produced significant power (equivalent to the 12-cell dodecagon) from only 6 cells;
- The cost of energy from an un-equal catamaran or 'Proa' with 8 cells is likely to be around 70% of that expected from the base-line 12-cell dodecagon design;

As the project was conducted relatively quickly at the Heriot Watt wave basin at 1:30 Scale, it was considered prudent to repeat the tests at MARIN at 1:15 scale with a bespoke Proa model.

4.2.5 1:15 scale testing of Proa, MARIN, 2012

The second MARIN test project was initiated in order to confirm the performance of the Proa design and to provide further engineering data for the FEED process. Key results are summarised as follows:

- 264 wave test runs were performed covering regular and irregular waves covering a range of the baseline resource direction;
- The device was quite insensitive to ballast, ring main pressure, draught and trim angle within a range around the design condition;
- Mooring loads did not exceed the design value. Mooring loads were actually lower than on the equivalent waves for the dodecagon;
- The operational envelope appeared to be limited to around Hs = 6.0 m in short (c. Tz = 7.5 s) waves but it is anticipated that the maximum wave height can be greater at longer wave periods although these were not tested due to wave maker constraints;
- A maximum average pneumatic power of 2.22 MW was recorded (over full-scale equivalent 15 minutes) in a sea state of Hs = 5.5 m / Tz = 7.5 s. The wave incidence was 22.5°. It was considered likely that the power output in the same sea state from 45° would be higher still;
- The maximum average pneumatic power of a single cell recorded was > 540 kW in same sea state as the maximum device power;
- The power matrix generated resulted in an annual pneumatic energy yield for the (uncapped) baseline test resource at 32.0 kW/m of 5.89 GWh;
- Short-crested seas significantly improved power capture in head seas by a factor of about 1.6 but were detrimental to power capture in non-head seas;
- The overall effect of short-crested seas was to negate the device's sensitivity to mean wave direction. In other words the power capture was roughly similar for all mean wave directions in short-crested seas;
- Alternative ring main arrangements did not improve power capture substantially;
- Varying damping over the device had minimal impact on power capture;

This test was the last in the series of overall device performance testing carried out on the AWS-III however further cell optimisation tests were carried out early in 2013 which indicated that large improvements in power capture can be gained by varying the cell geometry.

4.2.6 Diaphragm development

Development of the diaphragms commenced early in 2009 and continued until 2013. Work included materials development (reinforcement and coverings), geometry development, edge-fixing development and construction methodologies. Work was both desk-based and practical and included significant lab testing.

Results are reported throughout numerous documents, however the high-level outcomes of the programme are as follows:

- The S-Wave diaphragm concept, whilst attractive in terms of ease of manufacture of the diaphragms, was found not to be feasible using known materials due to the requirements for large strain in areas of the diaphragm. Research showed that strain should be limited to around 15% if a polymer component is to achieve a fatigue life in the order of 15 million cycles;
- Due to the strain limits referred to above, a 3-dimensional diaphragm shape is required. This was found to work well for power capture and was not sensitive to detailed geometry. What is important is to maximise the change in submerged volume;
- Use of a 3-D diaphragm requires the diaphragm to ‘crumple’ as it passes through the fixing aperture. This gives rise to severe flex-fatigue conditions, particularly if a thin material is used;
- Vertical loads in the diaphragm are considerable with in excess of 70kN / m being predicted for an 8 m high diaphragm submerged to a draft of 6 m;
- It is advantageous to match the inverted diaphragm shape to a supporting saddle to limit stresses under extreme waves;
- Vectran liquid crystal polymer fibres were found to have excellent tensile properties and fatigue resistance during laboratory tests. However these failed after a relatively short time during half-scale at-sea testing;
- The programme was suspended before a definitive material solution was found for the diaphragm;
- Manufacture of the diaphragm by way of gluing tailored panels over a former was found to be feasible;
- Glued panel joints performed well during half-scale at-sea tests;
- Edge attachment and sealing by way of a bolted flange and neoprene intermediate gaskets was found to be an acceptable solution for half-scale loads. A similar clamping solution but with a bolt-rope added was proposed for the full-scale diaphragm;
- Marine growth on the half-scale diaphragm was rapid and significant, however this did not appear to impede performance;

Overall however, whilst a large amount of research was carried out, a final solution to the diaphragm, either in shape or materials was not achieved. Significant further work will be required if the AWS-III technology is to be advanced.

4.2.7 Cassette development

Development of the cassette (see section 3.3) began in May 2010 and focussed on the construction of the cassette to achieve low cost and the attachment / change-out methodology. The key high-level results are summarised as follows:

- A sealed cassette comprised of a diaphragm and backing saddle provides the optimal means of assembling, testing, installing and exchanging diaphragms;
- There are significant issues with wave impact loading on the cassette in survival conditions when the diaphragm is deflated;

- FRP construction of the saddle is feasible up to full-scale however further work is required to define a feasible connection methodology for an FRP saddle to the steel hull;
- Several attachment and installation methodologies are feasible for a steel fabricated saddle which for a full-scale device would weigh around 70 tonnes;
- Power capture can be increased significantly by providing a greater swept volume in the diaphragm;
- The optimum method for cassette exchange is to use a bespoke H shaped barge capable of transporting two cassettes from a support vessel to an on-station AWS-III;
- Overall the cassette developed to become a major cost item in the AWS-III design and this impacted on the overall device economics;

At the point that development was suspended, alternative cassette solutions were being investigated. These included novel technology designed to eliminate the duplication inherent in the structural hull sitting behind a structural cassette.

4.2.8 FEED of FOAK, 2012/13

A front-end engineering design (FEED) study was largely completed for the proposed first-of-a-kind (FOAK) AWS-III device based on an 8-cell Proa design. This included development of hull scantlings and significant design and costing work by Damen Shipyards. Key outcomes are summarised as follows:

- The total weight of the AWS-III primary hull structure was > 2500 Tonne and the budget price from Damen for construction (including ancillary systems) was €14.4 million. Total costs did not reduce significantly as numbers increased, reflecting the fact that the costs were already low (at around €1,820/tonne;
- Costs were considered for construction in Eastern Europe and in China. Both were comparable when the additional costs of transport from the far-east were considered;
- The total cost of the cassettes was significant at >25% of the overall device costs;
- The novel turbine details were integrated with the design and found to be feasible. The cost of the turbine-generator sets was estimated at 18% of the total device costs;
- The mooring design assumed a 6-line taught nylon mooring and piled anchors. The total installed cost was > £6 million including contingencies;
- The overall cost of the FOAK, including design, construction system integration and deployment was > £20 million. This cost had increased from the original estimate of £16 million due to additional detail included during the FEED study;
- The diaphragm material selection and edge-clamping details were not finalised prior to suspension of the design;
- The dynamic instability (‘bubble’) issue was not resolved before suspension of the design.

Work on the FEED was suspended in April 2013 for commercial reasons.

4.2.9 Half-scale cassette demonstration, 2014

The half-scale cassette demonstration project was a development of an earlier project which set out to demonstrate a full-scale cassette at sea. The project was re-scoped as lessons were learned regarding the practicalities of the original proposed test and strategies developed for management of technical risk in the overall project. The key outcomes likely to be of interest to WES and other developers are wider than the project results. Points of interest are summarised as follows:

- A part-system test at full-scale in real sea conditions is challenging and effectively involves the design, construction and deployment of a vessel which has the functionality and survivability characteristics of the WEC, but which lacks some of the essential features of the WEC. Design work on the 'dumb barge' proposed to host the single AWS-III cassette revealed complexities and a cost-effective design was not found;
- The proposed durability tests at sea were found to be un-deliverable as a useful tool to inform diaphragm life predictions and failure modes for several reasons. Firstly, detailed inspection and recording of the condition of the diaphragm at sea is challenging and probably not feasible other than in very calm conditions. Secondly, failures are likely to occur in high wave conditions and under such conditions the damage is likely to be extensive, thereby masking the original cause of failure. Thirdly, failure of a single sample does not necessarily indicate a systemic problem in the design – multiple samples are required to establish this, and fourthly, it was not considered possible to measure the conditions (loads, etc.) experienced by the diaphragm leading up to any failure, and thus interpret the likely cause of failure in a way that could lead to design improvements. Accordingly, AWS Ocean decided to reduce both the scale of the proposed tests and the scope of what was intended from the tests and to supplement the programme with alternative ways to gather data;
- The feasibility of construction, installation and operation of a cassette in real sea conditions was proven at half scale;
- Laboratory and small scale testing of components does not necessarily give an accurate indication of likely performance at larger scale;
- The overall experience and practical learning in terms of marine operations, logistics, cost control and project management were as valuable as the test results in terms of moving the technology forward.

These tests will require to be repeated for any future variant of cassette design in order to de-risk this critical component before proceeding to full-scale deployment.

4.3 Electric Eel results

Work on the Electric Eel™ commenced in March 2008. This work included initial numerical modelling of performance using Abaqus finite-element analysis software, technical discussions with electro-active polymer (EAP) developers, consideration of the overall system challenges and some economic modelling of the system. Key high-level results are summarised as follows:

- Modelling of a flexible attenuator device is possible using advanced techniques in ABAQUS and appeared to give results consistent with theory. This allowed consideration of device parameters including scale, tube thickness and stiffness which in turn allowed some degree of optimisation for performance;
- Development of the EAP actuators for integration in the tube walls was considered very challenging, with particular caution expressed around the electrodes. Note that subsequent work on fatigue indicates that this may well be a limiting issue for any WEC which relies on straining materials to achieve power capture;
- Other challenging aspects of the design were seen as the integration of multiple sets of power electronics into the WEC design and the reliability issues that this could present;
- Overall, the economic performance of the device was not found to be as attractive as hoped. The estimated LCOE at a relatively immature stage in development was of the order of £300 /MWh (2008 prices) however there remained considerable uncertainties in this estimate.

Accordingly, AWS Ocean decided to prosecute the patent applications but not to risk further capital on the development of the concept until the EAP technology had been advanced further and proven in other applications.

5 Major technical decisions

AWS Ocean was established with the aim of delivering practical, affordable wave energy. AWS Ocean has never been 'inventor led' and we have always been prepared to challenge our technology positon where we considered that the overall aim was not achievable. Often this has led to tough decisions – and even tougher conversations with shareholders – however we believe that our commitment to finding a solution to commercial wave power, rather than focusing on commercialising a single technology has set us apart from other wave power technology developers.

Another characteristic of our journey is that as a small company we recognised the importance of using appropriate industrial partners for the key technology developments, whilst ensuring that we hire the best available engineers selected from relevant industries. This has meant that we have had access to the best available industrial knowledge and this has informed the decisions that we have taken.

The key technical decisions which have punctuated the AWS Ocean journey are tabulated below and discussed further in the sections that follow:

November 2006	Switch from linear generator PTO to hydraulic PTO
November 2006	Switch from high-volume pitching Waveswing™ to bottom-standing device
April 2007	Switch from high-volume device to evacuated low-volume Waveswing™
August 2008	Suspension of work on evacuated Waveswing™
February 2009	Adoption of 'S-Wave' technology as key focus
November 2010	Change from S-Wave in favour of AWS-III non-straining diaphragm technology
July 2012	Adoption of 'Proa' hull-form for AWS-III first-of-a-kind
April 2013	Suspension of investment in AWS-III programme
June 2014	Focus on small-scale market
August 2014	Re-commencement of Waveswing development programme

Discussion of the reasoning behind the key technical decisions outlined above is as follows:

5.1 Switch from linear generator PTO to hydraulic PTO

The Waveswing technology had always been conceived as using a linear generator for reasons of reliability and efficiency. The AWS MK 1 pilot plant employed a linear generator which was designed by Teamwork Technology (using WE Engineering BV and TU Delft expertise) and manufactured by Alstom. As development of the AWS pre-commercial demonstrator began in 2004, Alstom's large machines division in Rugby (who spun out from Alstom to become Converteam) were engaged in a collaboration to design a new, more efficient linear generator. This work continued until early 2007 when initial designs were frozen and both weights and cost provided by Converteam.

In parallel with the development of the generator, the AWS Ocean team were considering the issue of power shedding under extreme waves and of braking in the event of grid disconnection. The AWS MK 1 had used a set of water-filled dampers for this function, however whilst relatively cheap, these were found to involve excessive energy loss. Various alternative systems were investigated including hydraulics, for which AWS Ocean engaged Bosch Rexroth to carry out designs.

It was soon realised that the hydraulic braking system had to have all of the features of a PTO and with little additional cost could be adapted to provide the full functionality of an efficient PTO. Accordingly, the linear generator was seen as largely redundant as the essential hydraulic system could provide the PTO function without the additional costs of the linear generator.

Notwithstanding, the linear generator did hold out the possibility of higher efficiencies (around 80% overall across all wave spectra for the linear generator vs possibly 70% for hydraulics), however the weight of the linear generator at >300kg/kW and high costs associated with the design meant that the additional cost of the linear generator was not supported by the marginal gain in revenues.

The final decision to adopt the hydraulic PTO in favour of the linear generator was taken during a board meeting on 9 November 2006. Not all board members were in favour of the decision, with some believing that this was a retrograde step. This decision was primarily driven by economics, however with the in-hindsight benefit of full information in relation to the cost of the hydraulic PTO, this decision may not have been correct.

5.2 Switch from high-volume pitching Waveswing™ to bottom-standing device

The original intention of the Waveswing™ technology was that it would be a buoyant spar structure, tension tethered to the sea bed. The AWS MK 1 pilot plant deployed in 2004 was conceived as a fixed device largely to facilitate device deployment, anchoring and recovery, all by means of the submersible pontoon. This concept worked well for the pilot plant, albeit that the recovery was prejudiced due to rupturing of the buoyancy tanks caused by poor design.

As AWS Ocean approached the design of the pre-commercial demonstrator, the design basis reverted to a pitching (or at least non-fixed) design. Initial designs were provided by Teamwork Technology however it was soon realised that these designs did not provide sufficient air volume within the structure to enable operation of the device at the required wave periods. Work was carried out by Poseidon (Aberdeen-based offshore engineers) on behalf of AWS Ocean in order to modify the design to incorporate sufficient air volumes and this resulted in a significant increase in the length of the device, which now required in excess of 80m of water depth.

This large device presented a range of problems:

- The water depth requirements meant that deployment opportunities on the UK continental shelf were limited;
- Construction and transportation of the large structure was challenging;
- Overall costs, including the cost of anchoring were unacceptable.

The AWS Ocean team then considered a number of options including a reversion to the fixed submersible pontoon idea, but this time built from concrete and incorporating a surface-piercing access tower to facilitate maintenance.

Given the objectives current at the time – to demonstrate the technology in UK waters – and feedback from potential customers including SSE, the AWS Ocean board decided to adopt the bottom-standing concrete AWS as the basis of design for an EMEC prototype.

5.3 Switch from high-volume AWS device to evacuated low-volume Waveswing™

Work focused on the bottom-standing concrete AWS for 3 months with Fairhurst providing significant input to the design and costing of the device. By March 2007 however it was clear that this incarnation of the technology would be costly and more importantly, modelling showed that the energy yield from this design would be significantly below that previously expected. Drag losses associated with the 'wave shield' and low wave resource at the EMEC site were contributing factors.

A key factor that the team realised was that the high-volume AWS design had an inherent draw-back. To achieve a soft spring, the air volume within the device had to be in the region of 6 times the swept volume of the device. Sub-sea volume costs money, both in containment costs and in anchoring/ballast cost.

As a result the board asked the team to look at alternatives and the possibility of evacuating the interior of the AWS, thus eliminating the need for containment of large volumes of air sub-sea. The swept volume is provided by expanding and contracting the vacuum, whilst the counter-acting spring can be provided via the hydraulic PTO system. Accordingly, the total sub-sea volume can be reduced from in excess of 6 X swept volume to around 2.5 X swept volume – a significant gain. A further advantage of the evacuated system is that the mass of the floater can be significantly reduced, thus providing the opportunity for more broad-banded response.

Preliminary investigations indicated that the vacuum sealing would be technically feasible and that the PTO would indeed be capable of the restoring spring functions and a report was presented to the Board in April 2007.

A patent application for the new evacuated concept was lodged on 5 June 2007 and this forms the basis for all of the current Waveswing™ IP. The device then became simply known as the "Waveswing" from then on in order to differentiate from the high-volume AWS concepts.

5.4 Suspension of work on evacuated Waveswing™

The team focussed on the development of the evacuated Waveswing™ from early 2007 with the intention that a prototype device would be deployed at EMEC, targeted for 2009. Industrial partners were engaged including Bosch Rexroth, Avon Fabrications and others and within 12 months the conceptual design was complete and work commenced on the detailed design. However during this period, the numerical modelling of the system was further advanced with a new model being used. Further to this the wave energy resource available in typical locations was re-evaluated and estimates down-graded. The result was a progressive erosion in the predicted yield whilst as the engineering detail became clearer, estimates of capital cost escalated.

The team was aware of these issues, but was also alive to the fact that device scale and proportions could have a significant effect on the LCOE. Early May 2008 saw the team engage on a parametric modelling exercise which examined a range of device scales and evaluated the LCOE on a like-for-like basis. These results indicated that the smaller devices yielded better LCOE, however the smallest device modelled (a 6m diameter x 6m stroke device rated at 250kW) still had an LCOE in excess of £500/MWh at first farm scale (10 devices)[1].

It was known that the Waveswing™ design had a higher theoretical power capture capability than any other point-absorber design (due to the long stroke available and the fact that the absorber surface is close to the sea surface). It was also clear that the use of structural volume was highly efficient, however the cost of the internal nitrogen spring system, the PTO and other ancillaries rendered the device un-economic. Consideration was given to whether this was just a characteristic of Waveswing™ or whether the results were valid for other point absorbers and indeed other wave energy devices generally. The conclusion was that Waveswing was likely to have better LCOE than other point absorbers (and indeed other leading technologies of the time), notwithstanding the high capital costs.

The research work was presented to AWS Ocean's technical advisory committee ("TAC") and in August 2008 the TAC recommended suspension of work on the evacuated Waveswing™.

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[1] Note that further work in 2014 and 2015 indicates that significant LCOE improvements can be achieved by scaling down the Waveswing to around ½ the size previously considered.

5.5 Adoption of 'S-Wave' technology as key focus

Following suspension of the work on Waveswing™, the team engaged on a technology optimisation and innovation exercise in order to seek a potential solution to the challenge of producing practical affordable wave power.

This exercise began by considering the cost-drivers for the Waveswing™ and the limitations of the system in engineering terms. It was recognised that the Waveswing™ design was complex and that the high component count and sub-sea location combined to drive both capital and operating costs to an unacceptable level. Further to this, it was recognised that countering the hydrostatic spring (caused by buoyancy) inherent in any heaving wave energy device presents a challenge and that a novel and cost-effective means of meeting this challenge could be game-changing for the viability of wave energy converters.

Numerous options were considered including some options for devices with 'hydrostatic gearing' which although not recognised at the time, are now believed to provide the basis for more economic point absorber technology. The exercise led the team to consider the use of flexible 'balloon' configurations in place of the telescopic can of the Waveswing™, and the use of such absorbers on a floating host structure. Logical development of the designs led the team to a design which incorporated multiple flexible absorbers and used an air turbine PTO.

The team then realised the similarities between the new concept and the original CLAM design developed by Norman Bellamy's team at Lanchester Polytechnic in the 1980's. A high-level economic appraisal based on Bellamy's work indicated that the device could have a sector-leading LCOE and accordingly, the team sought to understand the device further and a detailed diligence exercise was commenced.

During diligence, contact was made with Dr Don Turner and Dr Les Duckers, both of whom were involved with the early CLAM development. Coincidentally, Duckers & Turner had just applied for patent in respect of a development to the CLAM which they believed would improve the performance of the diaphragms. This was known as the 'S-Wave' due to the S-shaped sides introduced to the diaphragm profile.

The diligence work (which included a review of structural and mooring costs by Noble Denton) concluded that the device had significant prospects for a LCOE competitive with offshore wind. Meantime, AWS Ocean had secured rights to the new IP which would protect any future investment. Further to this a technology assessment carried out in line with DNV guidelines indicated that the development risk was limited to that inherent in the diaphragm.

Accordingly, the 'new' device design was presented to the AWS Ocean Board in February 2009 and a decision was taken to adopt the S-Wave as the lead technology prospect for the company based on the following fundamentals:

- Theory and analytical work showed that the device had a realistic prospect of delivering a low LCOE;
- The technology risk in the concept was perceived to be low and the remaining risk manageable;
- New IP was available to protect revenues necessary to repay investment in the technology;

Market acceptability, manageable technology risk and protectable IP are typical fundamental criteria for an early stage investment decision in any new technology development.

5.6 Change from S-Wave in favour of AWS-III non-straining diaphragm technology

As noted above, the key risk in the S-Wave technology was perceived to be the diaphragm and this is where work was focussed for much of 2009 and 2010. The company developed cutting-edge techniques for finite-element analysis of non-linear elastic structures and used these techniques to generate a set of requirements for the diaphragm materials. A key requirement of the S-Wave design was that the diaphragms should strain (i.e. stretch) up to 40% in some areas and analysis showed that these strain cycles could be repeated up to 3.5 million times in a year. From this a duty-cycle requirement of tensile strain to 40% for 15 million cycles was adopted in order to allow a 5 year life.

Research into the performance of elastomers supported by leading UK suppliers and academia rapidly established that the duty-cycle was extremely challenging. Several elastomer compounds were developed but all failed under test at only a few thousand cycles. Further research indicated that the duty-cycle may not be achievable with any known material. During this time the team also completed the 1:9 scale tests on Loch Ness using the S-Wave design and diaphragm failures were experienced after only a week of operation.

As a result, AWS Ocean began to question the possibility of a solution to the diaphragm problem and decided to seek wider advice. To achieve this AWS Ocean organised a symposium involving as many of Europe’s leading elastomer experts as possible. The meeting was held in September 2010 and attended by 14 experts from industry and academia. The problem was presented to the meeting and the universal conclusion was that there was no known solution to the required duty cycle. Instead the meeting recommended that AWS Ocean consider a 3-dimensional diaphragm which would achieve the necessary swept volume without requiring significant strain (i.e. less than 5%).

Following the advice of the elastomer symposium, AWS Ocean was unclear as to what the effect of changing to a 3-D diaphragm design might be on wave power capture. Accordingly, the team proceeded to carry out a set of tests at Strathclyde University Kelvin Hydrodynamics Lab tank to compare the S-Wave performance with an equivalent 3-D design. The results showed a significant improvement in power capture resulting from the change. The team also discussed the production of a 3-D diaphragm with two separate suppliers and this was considered to be feasible.

Accordingly, on the basis that the risks in achieving a technical solution were perceived as lower, together with the improvements in performance, the S-Wave design was abandoned in favour of a planar-sided, 3-dimensional diaphragm.

5.7 Adoption of 'Proa' hull-form for AWS-III first-of-a-kind

The next significant change in the AWS-III technology programme was in relation to the plan-form of the hull. The original work by Bellamy's team had determined that a 12-cell structure arranged as a dodecagon was optimal for structural and performance reasons. The AWS Ocean team adopted this design initially as there was no reason to question it, however the results from the Loch Ness 1:9 scale S-Wave tests and further evidence from 1:15 scale AWS-III tests carried out at MARIN showed significant variation in the capture effectiveness of the various cells. Further to this, naval architecture work and assessments of build-ability of the hulls (measuring 60m in diameter) gave rise to further concerns regarding the dodecagon shape.

It was therefore decided to investigate alternative hull plan-forms in order to discover if performance could be improved whilst construction difficulty (and hence cost) could be reduced. Tests were carried out at Heriot Watt university tank during a 12 week period from April 2012 during which time numerous hull-forms were tested. The performance results, prospective build costs and other practicalities including mooring requirements and directionality were considered for each and as a result the 'Proa' design (Figure 8) was selected as the preferred shape for a First-of-a-kind (FOAK) demonstrator unit.

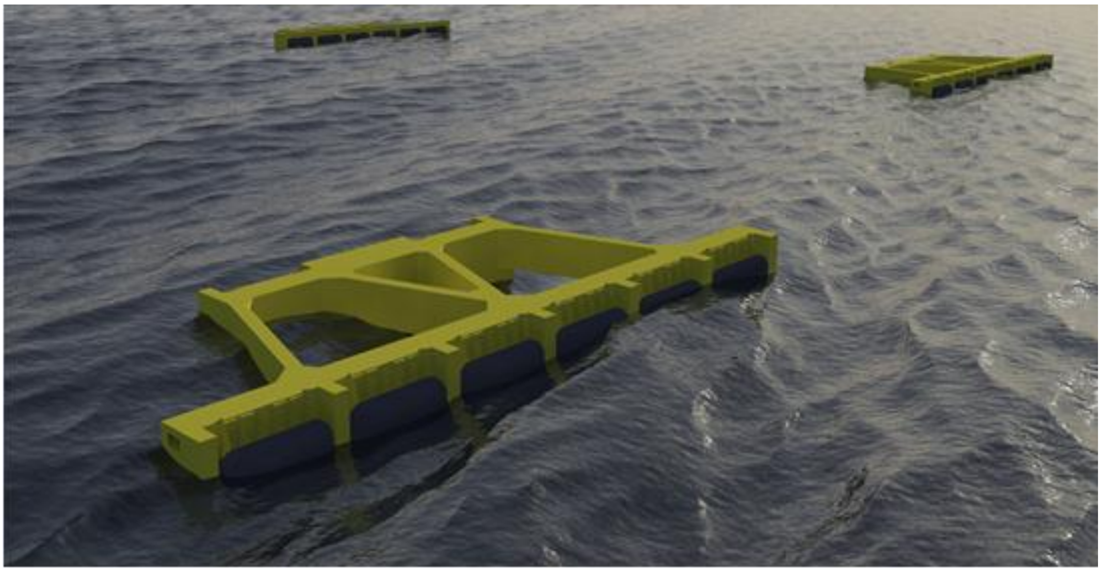


Figure 8 – the 'Proa' AWS-III configuration

As noted above, this decision was driven by overall cost of energy and build practicality. This decision was endorsed by AWS Ocean's major shareholders and potential customers.

5.8 Suspension of investment in AWS-III programme by AWS investors

Following adoption of the Proa hull shape, the team executed a further high-quality 1:15 scale performance test at the MARIN tank facility. Unfortunately, this delivered results lower than indicated by the Heriot Watt trials. Meantime, detailed naval architecture design had resulted in increases in the hull volume and weight in order to counter dynamic instability issues caused by the moving buoyancy of the diaphragms (known in AWS Ocean as the ‘bubble effect’). These factors led to an increase in the projected LCOE.

Co-incidentally, utility companies had begun to withdraw interest from marine renewables projects and further delays to grid development indicated slippage to the potential programme for Costa Head. These factors led to increased concern by AWS Ocean’s investors who challenged the AWS Ocean team to demonstrate a viable route to market for the AWS-III technology, setting a technology review date of March 2013.

The team engaged in further optimisation activities whilst in parallel, a detailed FEED exercise was completed including costing of the hulls by Damen Shipyards. The resulting data was used to populate a detailed cost of energy model to support the commercialisation plans.

The AWS Ocean team was able to demonstrate to the review panel that the AWS-III could meet the cost of energy targets, however notwithstanding, in May 2013 AWS Ocean investors informed the company that they did not intend to invest further.

5.9 Re-commencement of Waveswing development programme

The decision to re-commence development of the Waveswing™ programme stemmed from two key developments:

- Firstly, it became clear that the feasible route to market for any wave energy technology was likely to be via small scale devices capable of meeting isolated power needs. Market research by AWS Ocean indicated that this could indeed represent a large opportunity, both in terms of value and importantly, in terms of the numbers of devices that could be installed. This is also regarded as a prudent step in the path towards production of larger devices.

- Secondly, on reviewing the previous work on Waveswing™ it was realised that the potential for significant innovation which would eliminate the expensive gas-spring / hydraulics combination. Investigation of this innovation confirmed the feasibility and a check on potential economics indicated a very significant improvement in the potential cost of energy from this new variant of the Waveswing™ technology.

Accordingly, it was decided to invest further effort in a concept design and more detailed modelling within the context of a renewed development programme based on novel (and patentable) IP.

6 Patent applications and other IP

During the past 11 years of R & D, AWS Ocean has filed applications for patent protection for numerous ideas. We also have an invention disclosure register, currently standing at 54 individual inventions. A summary of the patent applications and their current status is presented in Table 1 below:

AWS Ref	Subject matter	Priority date	Status
P100	Waveswing MK 1		Abandoned
P200	Waveswing MK 1	4/9/1998	Expires 4/9/2018
P300	Vacuum Waveswing	05/06/2007	Granted, various
P400	Electric Eel	28/02/2008	Granted, various
P500	S Wave	28/02/2008	Abandoned
P600	Self-drilled Pile	06/08/2008	Granted, UK
P700	Hosepump PTO	16/11/2009	Abandoned
P800	Combined Mooring and PTO	16/11/2009	Abandoned
P900	Saddle	11/03/2010	App, national phase
P1000	Not used	n/a	
P1100	Phase Change Gas Spring	30/10/2012	Abandoned
P1200	AWS-III Diaphragm	12/10/2012	App, national phase
P1300	AWS III System	08/08/2013	App, national phase
P1400	AWS-III Cassette	12/10/2012	App, national phase
P1500	Proa AWS-III	n/a	Not lodged
P1600	Waveswing with combined vacuum and hydrostatic gearing	13/08/2015	Application

Table 1 – Summary of AWS registered IP

AWS Ocean is continuing to develop new IP for the wave energy sector and will welcome the opportunity to work with Wave Energy Scotland to develop and commercialise this in the future.

7 Conclusions

AWS Ocean and predecessor organisations have been carrying out R & D to find a solution to providing practical, affordable wave power for more than 20 years. During this time we have accumulated a vast amount of experience and examined numerous concepts – many more than are reported in this report. Our focus has been to find solutions, not simply to prove that a single invention works.

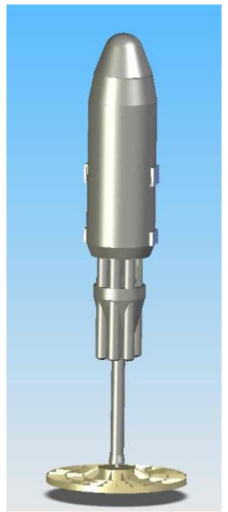
As we all accept, wave energy is a difficult challenge. Many thousands of man-years have been invested in research without yet producing an economic solution. Many hundreds of concepts have been examined, however on closer inspection many of these are simply replications of earlier concepts with some subtle design changes. With a deeper understanding of wave energy, it can be seen that even apparently quite different devices are in fact just different embodiments of the same principle – for example the Salter Duck and the AWS-III are very close in principle, despite being totally different in engineering implementation.

AWS Ocean is therefore of the firm view that the likelihood of finding a game-changing and fundamentally novel wave energy absorber concept is very low. Instead, what is needed is to develop a better understanding of the fundamental drivers of cost and economic performance for wave energy converters and for this knowledge to be used to optimise systems so as to produce low-cost wave power.

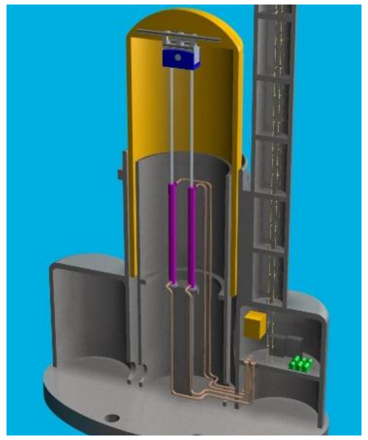
AWS Ocean recommendations for the future focus of wave power R & D work will be presented in report 15-013 to be delivered in September 2015.

Appendix A – Archimedes Waveswing™ development time-line

May 04
AWS MK1 pilot plant
Deployed off
northern Portugal

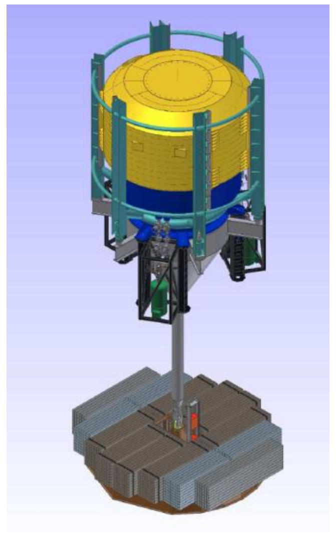


Dec 05
MKII developed by AWS (90m water depth).
Pitching system, compliant
Twin wall structure, partly concrete filled
Tubular steel leg
Steel tray for water base
12m diameter, 12m stroke
Linear generator

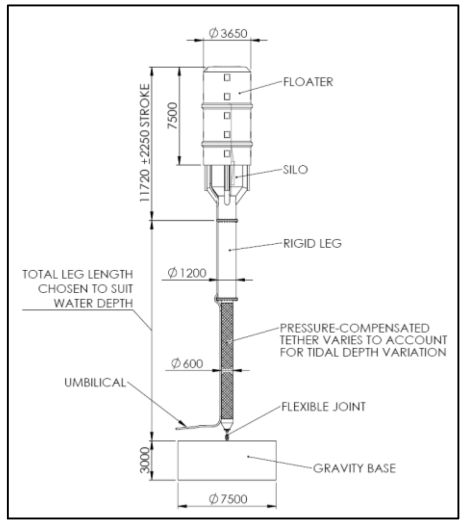


Dec 06
Design for shallower water
developed to include:
concrete base,
hydraulic PTO,
rolling rubber seal

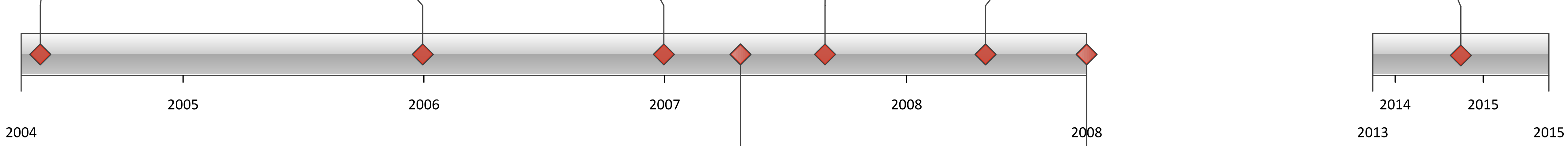
Aug 07
High pressure gas spring developed,
vacuum inside silo,
designed for 50m water depth,
6m diameter and 6m stroke,
Ancilliaries in pods on leg,
concrete caisson gravity anchor



Apr 08
Removable head,
parallel hydraulics system,
steel gravity anchor,
8m diameter and 3.4m stroke,
ancilliaries in head



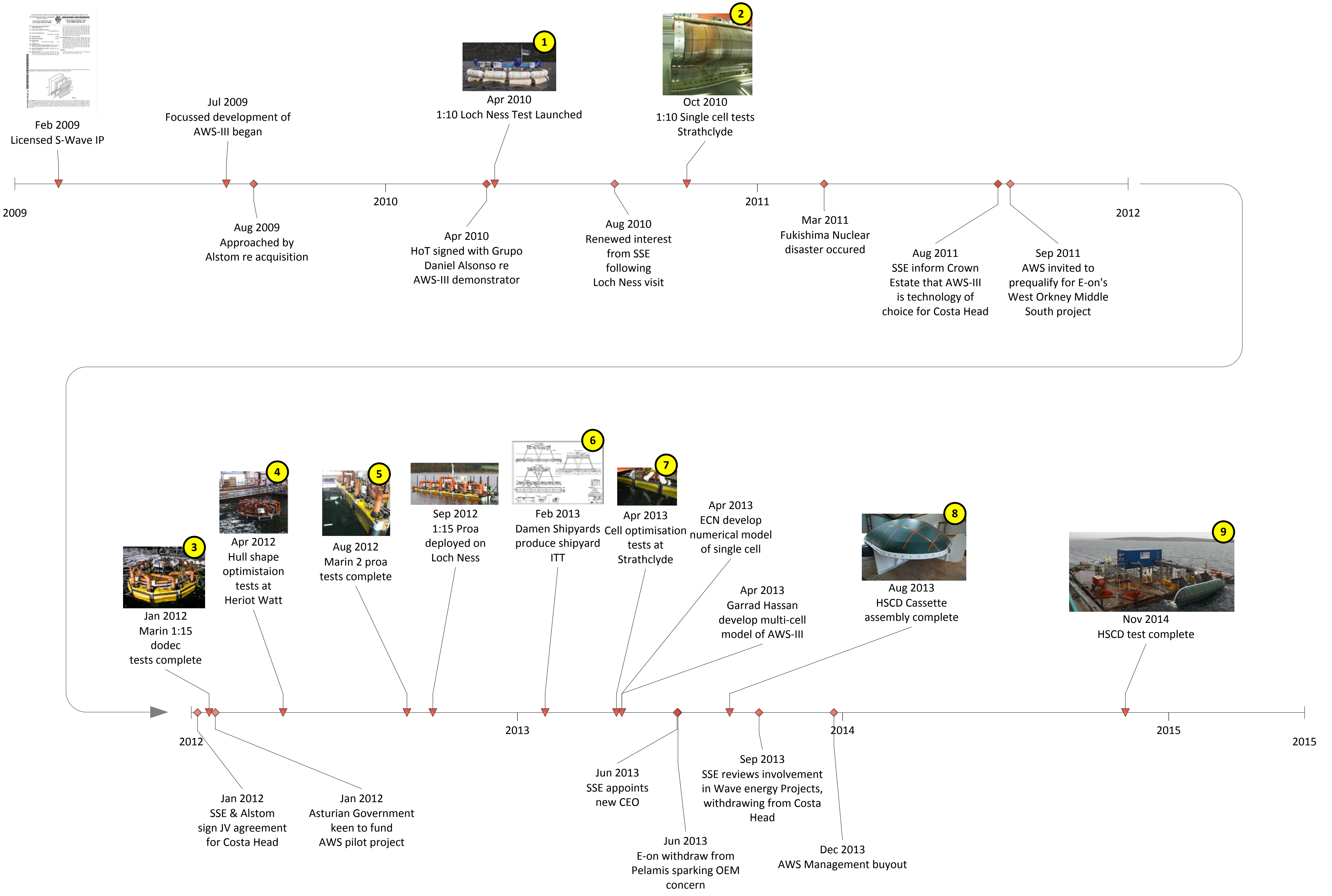
2014
Waveswing MK IV
Reduced scale
Hydrostatic gearing allows
simplified system.
New patent application



Apr-07
High level analysis:
design uneconomical.
Step change in design required

2008
Further optimisation required

Appendix B – AWS-III development time-line



Feb 2009
Licensed S-Wave IP

Jul 2009
Focussed development of
AWS-III began

Aug 2009
Approached by
Alstom re acquisition

Apr 2010
1:10 Loch Ness Test Launched

Apr 2010
HoT signed with Grupo
Daniel Alsonso re
AWS-III demonstrator

Aug 2010
Renewed interest
from SSE
following
Loch Ness visit

Oct 2010
1:10 Single cell tests
Strathclyde

Mar 2011
Fukishima Nuclear
disaster occured

Aug 2011
SSE inform Crown
Estate that AWS-III
is technology of
choice for Costa Head

Sep 2011
AWS invited to
prequalify for E-on's
West Orkney Middle
South project

Jan 2012
Marin 1:15
dodec
tests complete

Jan 2012
SSE & Alstom
sign JV agreement
for Costa Head

Jan 2012
Asturian Government
keen to fund
AWS pilot project

Apr 2012
Hull shape
optimistaion
tests at
Heriot Watt

Aug 2012
Marin 2 proa
tests complete

Sep 2012
1:15 Proa
deployed on
Loch Ness

Feb 2013
Damen Shipyards
produce shipyard
ITT

Apr 2013
Cell optimisation
tests at
Strathclyde

Apr 2013
ECN develop
numerical model
of single cell

Apr 2013
Garrad Hassan
develop multi-cell
model of AWS-III

Jun 2013
SSE appoints
new CEO

Jun 2013
E-on withdraw from
Pelamis sparking OEM
concern

Aug 2013
HSCD Cassette
assembly complete

Sep 2013
SSE reviews involvement
in Wave energy Projects,
withdrawing from Costa
Head

Dec 2013
AWS Management buyout

Nov 2014
HSCD test complete

Appendix C – AWS-III R & D project route-map