New Zealand Multi-Mode Technology Demonstration at the US Navy's Wave Energy Test Site

2018

Final Scientific and Technical Report

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1. EXECUTIVE SUMMARY

The objective of the project is to redeploy the Wave Energy Technology – New Zealand (WET-NZ and now known as Azura) device that was tested at the NNMREC test site in 2013 at the United States Navy's Wave Energy Test Site (WETS). The goal is to conduct open-ocean, grid connected testing for a period of up to 12 months to 1) optimize energy capture and 2) validate LCOE model. The project is focused on collecting power and other performance data to help validate computer simulation tools, develop ocean operations experience, and validate hydraulics as a viable means of energy conversion. The project was completed in accordance with the original objectives. The project leveraged the existing infrastructure at WETS and other sources of private and public funding to develop a large data set that will be used by NWEI, the National Renewable Energy Lab, and Sandia National Labs to continue the development and refinement of analytical tools for the marine and hydrokinetic industry. By utilizing the Azura device that was previously tested at NNMREC in 2012, the project was able to focus the limited project budget on improving the design to withstand the rigors of a 12-month deployment. A part of the project, a technical paper was published comparing test data to computer simulation. More information on this paper is shown in Section 5.

2. ACCOMPLISHMENTS

The project goals are as follows:

1) Advance understanding of innovative marine and hydrokinetic (MHK) technologies and identify areas of performance improvement that will benefit this emerging industry as a whole.

2) Support deployment of innovative MHK systems which can lower the LCOE below a local "hurdle "rate.

3) Compile, analyze, and disseminate information to accurately characterize and evaluate the performance of the MHK technologies and to integrate information into numerical models to establish baseline cost of energy, assess key cost drivers, and identify cost reduction pathways.

The project resulted in three major accomplishments:

1. **Validation of Computer Simulations** - The project resulted in the modification, deployment and testing of the Azura wave energy device for a period of 12 months. The data that was collected was compared to computer simulation models to compare predicted performance with actual data. A very high degree of correlation was established. More details are shown in Section 5. This accomplishment will give NWEI the confidence to move forward with the design of a Commercial Prototype using the computer simulation techniques validated in this project.

2. **Demonstration of Robust Design** – The Azura device was deployed for 12 months and demonstrated a 98% availability. This validates that a hydraulic power conversion system can deliver affordable, reliable, and robust energy conversion for marine energy devices. This validation of hydraulics in this application could have broad benefit throughout the industry.

3. **Marine Operations Experience** – The 12-month deployment resulted in the development of a wealth of information related to marine operations. In order to become commercially viable,

wave energy devices must be able to survive and be maintained in the harsh marine environment. While the 12-month deployment only represents a fraction of the required 20-year life of a commercial device, the experience provided an initial insight into what will be required. Further, the project provided a strong understanding of how to do business in Hawaii and at a US military installation. This experience will provide valuable in the next phase of development as Azura is tested at commercial scale at the deep water test site.

3. PROJECT ACTIVITIES

The Project consisted of the following tasks and subtasks:

Task 1.0: Project Management and Reporting

Task 2.0: Mooring System Design

Task 3.0: Grid Interconnection

Task 4.0: Deployment

Task 4.1: Deployment Plan

Task 4.2: Permitting and NEPA

Task 4.3: Deployment

Task 5.0: Testing. Evaluation, and Dissemination

Task 5.1: Data Acquisition Plan

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Task 6.0: Device Modifications

Task 6.1: Hull

Task 6.2: PowerPod Structural Modifications

Task 6.3: Float Modifications

Task 6.4: Hydraulic System Modifications

Task 6.5: Power and Control System Modifications

A summary of the project activities is shown below by Task and Subtask.

Task 1.0: Project Management and Reporting

This task includes overall project management. Reports and other deliverables as required by the contract were provided in accordance with the Federal Assistance Reporting Checklist.

Task 2.0: Mooring System Design

The objective of this task was to complete the detailed design and analysis of the mooring system for the Hawaii Project using the existing anchor configuration. The task included the design a mooring design which is optimized to minimize mooring loads, a loads analysis which considers all peak loads for the WETS site, the diameter and length of mooring lines, type and size of all required chain and shackles, number, type, and location of subsurface floats if required. This task was completed with the assistance of Sound and Sea Technologies ("SST"), which designed the moorings to meet the requirements as described in the Navy's "30 Meter Site Report". Following deployment of the Azura device it was observed that there was too much slack in the landward facing mooring leg. The mooring system was redesigned by SST and the modification was completed by Sea Engineering on January 6-8, 2016 to correct the problem. Following the mooring modification, the power output of the Azura device increased and overall mooring loads were reduced.

Task 3.0: Grid Interconnection

The objective of this task was to design a shore station grid-export power system. This work was completed with the assistance of Williwaw Engineering (Dr. Terry Lettenmaier). Prior to contract award it was the intent to utilize the existing grid interconnection hardware. After contract award, NWEI learned that the existing grid interconnection equipment (inverters, breakers, etc.) were insufficient to support the planned operations and testing of the Azura device. NWEI was able to develop an interconnection system which adequately met the project requirements. NWEI applied for and obtained an interconnection agreement with Hawaiian Electric Corporation.

Task 4.0: Deployment

Task 4.1: Deployment Plan

The objective of this task is to develop a deployment plan in accordance with all applicable Navy regulations for deploying and removing the Hawaii Project. This task was completed per the original assumptions and included the development of the following documents to support the deployment of the Azura device at WETS:

1. Safety Plan
2. Emergency Response Plan
3. Work Plan – Power Cable
4. Work Plan – Dive and Marine Ops Safety Plan
5. Work Plan – Installation
6. Work Plan – Recovery

These plans were submitted to and approved by the Naval Facilities Command ("NAVFAC") pursuant to the terms of the Cooperative Research and Development Agreement ("CRADA") that was developed with NAVFAC.

Task 4.2: Permitting and NEPA

The objective of this task is to support the Navy's efforts to obtain the permits required to deploy the WET-NZ device at the WETS site. This task was completed per the original assumptions and included the development of the following attached documents to support the permitting of the Azura device testing at WETS:

1. Ecological Assessment
2. CATEX

NWEI also obtained the required Private Aids to Navigation permit from the Coast Guard. Further, NWEI worked with the DOE to support the development of the required NEPA documentation.

Task 4.3: Deployment

The objective of this task is to deploy the device and moorings in accordance with the design specified in Task 2 and the Deployment Plan. This task was completed per the original assumptions and in accordance with the plans as described above. The only exception is the mooring problem described in Task 2.0 above. A presentation describing the deployment process was made at the Oregon Wave Energy Trust's Ocean Renewable Energy Conference in Portland, Oregon on July 15, 2015. The presentation is available at the following site:

http://oregonwave.org/oceanic/wp-content/uploads/2015/08/ORE-X-Session-1C-Steve-Kopf.pdf

A four-minute video showing the deployment and operation of the device at WETS is shown in the following video:

https://www.youtube.com/watch?v=e2Z33KcFn20

Task 5.0: Testing. Evaluation, and Dissemination

Task 5.1: Data Acquisition Plan

The objective of this task is to *work collaboratively with project partners and Hawaii National Marine Renewable Energy Center (HNMREC) to develop a detailed test plan.* This task was completed per the original assumptions. A detailed test plan was submitted to DOE (and available on DOE's Marine and Hydrokinetic Data Repository (MHKDR)), University of Hawaii, and NAVFAC prior to testing.

Task 5.2: Data Collection

The objective of this *to collect the data as described in the Test Plan (Task 5.1).* This task was completed per the original assumptions. Prior to deployment there were several tests of the PowerPod and the grid interconnection system. The following test reports were developed and submitted to DOE (and available on DOE's MHKDR):

1. Test Report – Dry Testing
2. Test Report – Low Power
3. Monthly Test Report – June 2015
4. Monthly Test Report – July 2015
5. Monthly Test Report – August 2015

6. Monthly Test Report – September 2015
7. Monthly Test Report – October 2015
8. Monthly Test Report – November 2015
9. Monthly Test Report – December 2015
10. Monthly Test Report – January 2016
11. Monthly Test Report – February 2016
12. Monthly Test Report – March 2016
13. Monthly Test Report – April 2016
14. Monthly Test Report – May 2016

Task 5.3: Data Analysis

The objective of this task is to analyze the data collected in Task 5.2 and to develop a summary report of relevant results. This task was successfully completed per the original assumptions and demonstrated twelve months of reliable prototype Azura operation at the WETS 30 m site. A complete summary of test results was developed and submitted to DOE (and available on DOE's MHKDR).

Specific conclusions that can be drawn from the results are as follows:

- The device survived sea conditions with Hm0 as high as 4.5 m and individual waves as high as 7.5 m during the test period
- High availability was demonstrated for the device during the test period, with over 98% availability during several months. The device was capable of operation throughout the ten-month period, with the exception of one 12 day period after a hydraulic hose became loose.
- Power performance of the device was measured with constant motor displacement operation. Output power always increased with decreasing Te for the same Hm0, with the highest power for a given Hm0 always occurring in the minimum Te bins.
- While the full range of PTO hydraulic motor displacement settings were tested over a long period of time, the results show that motor displacement only had a small effect on device output power.
- Output power of the device was not substantially higher when PI control of PTO hydraulic motor displacement was used than when constant motor displacements were used.
- PTO efficiency was approximately 65% to 70% at higher (greater than 1500 W) output power.
- RAO results show that hull motion noticeably increased at wave periods longer than about 6 s, and the greatest float angle movement occurred at 4 s to 5 s wave periods. These results are consistent with the natural periods of the hull and float; increased hull motion is expected at periods longer than the coupled hull-float resonant period of 6 s, and the greatest float motion is expected at periods between the float resonant period of 3 s and the coupled hull-float resonant period of 6 s. The RAO results also show that there is very low pitch and roll motion of the hull across the full range of wave periods.
- RCW results show that the prototype device is most effective at producing power from wave periods of four seconds or less in the spectra, and does not produce significant

power for wave periods longer than six or seven seconds. This is consistent with the natural periods of the device; the greatest power production is expected at longer periods than the float natural period (3 s) and shorter periods than the coupled hull-float natural period (6 s). Since the bulk of the wave energy at the test site occurs at wave periods longer than six or seven seconds, this poor long period response greatly limited power production for this prototype at the WETS site. This is an expected result, however, because the prototype Azura is a small-scale prototype device that, due to its short resonant periods, was not expected to be well tuned to the wave periods at WETS. A larger full scale device with longer resonant periods would be better tuned to the ocean conditions at the site.

Task 5.4: LCOE Model Updates

The objective of this task is to update the LCOE model based on the data collected at the WETS site. This task was completed per the original plan.

Task 5.5: Dissemination Plan

The objective of this task is to develop and execute a comprehensive dissemination plan to complement and extend ongoing and existing communications activities, as follows:

- The principal investigators will continue their program of technical and business presentations with presentations at US national and international conferences;
- The project team will update the WET-NZ website to give full coverage of both US
- and NZ activities;
- NWEI will continue the practice of issuing press releases to publicize significant milestones in the project. NWEI already keeps updated lists of relevant energy and economic journalists, to whom press releases are circulated.

This task was completed and publicly available documents are described in Section 4.0 of this report.

Task 6.0: Device Modifications

Task 6.1: Hull

The following modifications were made to the hull prior to deployment at WETS:

- Design and install conduits for all data acquisition cables;
- Design and install a conduit for the interconnection cable;
- Design and modify the interconnection cable termination bracket based on specific needs of WETS;
- Modify upper flanges of Hull and reassemble for better alignment with PowerPod;
- Pack and ship Hull to HI;
- Apply anti-fouling bottom paint suitable for Hawaii's environment.

This task was completed per the original assumptions.

Task 6.2: PowerPod Structural Modifications

The following modifications were made to the PowerPod prior to deployment at WETS:

- *Remove PowerPod from Hull at Toledo Shipyard in Oregon;*
- *Ship PowerPod to New Plymouth, NZ;*
- *Modify flange design;*
- *Re-assemble structure;*
- *Re-assemble hydraulics and electrics into structure;*
- *Fit any new instrumentation to unit and test;*
- *Install new float (See subtask 6.3);*
- *Set up on vertical test rig*
- *Dry test for 60 hours;*
- *Inspect and evaluate components;*
- *Disassemble and package for shipping to Hawaii;*
- *Ship to Hawaii.*

This task was completed per the original assumptions.

Task 6.3: Float Modifications

The following modifications were made to the float prior to deployment at WETS:

- *Modify Float design;*
- *Manufacture new or modify existing Float;*
- *Apply primer to float;*
- *Reinstall the Float to the PowerPod;*
- *Dry test to assure proper alignment;*
- *Measure bearing losses;*
- *Apply anti-fouling paint in Hawaii prior to redeployment.*

This task was completed per the original assumptions.

Task 6.4: Hydraulic System Modifications

The following modifications were made to the hydraulic system prior to deployment at WETS:

- *Remove Hydraulic System from PowerPod;*
- *Ship hydraulic components to New Plymouth, NZ;*
- *Strip and access all components;*
- *Remove auxiliary hydraulic circuits;*
- *Replace hydraulic motor with electronic control model;*
- *Make up new control cabinet for motor controls;*
- *Bench test and tune;*
- *Reinstall components in PowerPod.*

This task was completed per the original assumptions. A test report summarizing dry testing of the PowerPod was delivered to DOE (and available on DOE's MHKDR).

Task 6.5: Power and Control System Modifications

The following modifications were made to the power and control system prior to deployment at WETS:

- *Design and modify the device to allow connection to subsea cable and local grid;*
- *Design, fabricate, and install Shore Station;*
- *Interconnect shore station to the MCBH grid;*
- *Test functionality of the Shore Station.*

This task was completed per the original assumptions.

Task 6.6: Mooring System Modifications

The following modifications were made to the power and control system prior to deployment at WETS:

- *Modify existing procure new Subsurface Floats;*
- *Modify existing and procure new Mooring Lines;*
- *Apply anti-fouling paint;*
- *Ship all items to Hawaii*

This task was completed per the original assumptions.

4. PRODUCTS

The following products were developed as part of the project:

Publications

A paper titled "WEC-Sim Model Validation of the Azura Prototype" was presented at the 2016 Marine Energy Technology Symposium in Washington, DC on April 26, 2016. The paper is available at the following site (username and password are both METS):

http://events.pennwell.com/nha2016/Public/Cust_DownloadHandout.aspx?Task=Speaker60970_Session15733_1.pdf

Presentations

A presentation was made at the DOE Water Power Program Peer Review meeting held February 24-28, 2014 in Washington, DC. The presentation is available at the following site:

http://www.nrel.gov/docs/fy14osti/61854.pdf

A presentation was made at the Oregon Wave Energy Trust's Ocean Renewable Energy Conference in Portland, Oregon on July 15, 2015. The presentation is available at the following site:

http://oregonwave.org/oceanic/wp-content/uploads/2015/08/ORE-X-Session-1C-Steve-Kopf.pdf

A presentation was made at the International Marine Renewable Energy Conference in Washington, DC on April 25, 2016. A copy of the video presentation can be found at:

https://www.youtube.com/watch?v=e2Z33KcFn20

Website

NWEI maintains the following website: www.azurawave.com

Multimedia

The deployment of the device at WETS is shown in the following video:

https://www.youtube.com/watch?v=LAqNOTSoNHs

A four minute video showing the deployment and operation of the device at WETS is shown in the following video:

https://www.youtube.com/watch?v=e2Z33KcFn20

A one minute summary of the operation of the device is shown in the following video:

https://www.youtube.com/watch?v=7LNdRqxhY3o

A news piece produced by KITV is shown in the following video:

https://www.youtube.com/watch?v=YRd3PZNnnF0

Press

The following press articles were published following deployment of the device at WETS:

Click Green "First Wave Energy Device Delivers Power to Military Base" June 9, 2015
http://www.clickgreen.org.uk/news/international-news/126134-america%5Cs-first-wave-energy-device-delivers-power-to-military-base.html

Tidal Energy Today "Azura Device Powers Military Base in Hawaii" June 9, 2015
http://tidalenergytoday.com/2015/06/09/azura-wave-energy-device-powers-military-base-in-hawaii/

Clean Technica "US Marines Get New Wave Energy Device" June 12, 2015
http://cleantechnica.com/2015/06/12/us-marines-get-new-wave-energy-device-looks-like-loch-ness-monster/

Tidal Energy Today "VIDEO: Azura Wave Device" June 12, 2015
http://tidalenergytoday.com/2015/06/12/video-azura-wave-energy-device/

Environews TV "Americas First Grid Connected Wave Power Station" June 12, 2015
http://environews.tv/world-news/americas-first-grid-connected-wave-energy-conversion-project-comes-online/

Biz Journals "Wave Energy Device Activated Off Hawaii's Kaneohe" June 16, 2015
http://www.bizjournals.com/pacific/blog/morning_call/2015/06/wave-energy-device-activated-off-hawaii-s-kaneohe.html

Hawaii Clean Energy "Wave Energy Device Activated Off Kaneohe" June 16, 2015
http://www.hawaiicleanenergyinitiative.org/wave-energy-device-activated-off-hawaiis-kaneohe-bay/

Renewable Energy Magazine "Azura Wave Device Deployed at US Navy Test Site" June 18, 2015
http://www.renewableenergymagazine.com/article/azura-wave-energy-device-deployed-at-us-20150618

Surfer Magazine "Power Surfing: The Azura" June 29, 2015
http://www.surfermag.com/features/power-surfing-azura/#EljJ0ZJsgJCr8BRV.97

DOE EERE "Innovative Wave Power Device Starts Producing Power" July 6, 2015
http://energy.gov/eere/articles/innovative-wave-power-device-starts-producing-clean-power-hawaii

reNEWS "Azura Faces Up to the Test" July 7, 2015
http://renews.biz/91354/azura-faces-up-to-the-test/

GIZMag "Azura Wave Energy Deployed in Hawaii" July 8, 2015
http://www.gizmag.com/azura-wave-energy-system-hawaii/38371/

Think Progress "This 45 ton Buoy Might Change the Way You Get Power" July 9, 2015
http://thinkprogress.org/climate/2015/07/09/3678554/hawaii-adds-wave-power/

American Institute of Chemical Engineers "Oahu, We Have Liftoff" July 24, 2015
http://www.aiche.org/chenected/2015/07/oahu-we-have-liftoff-first-wave-energy-device-power-hawaiis-grid

Coastal/Energy Environment "Azura Captures the Motion of the Ocean" July 26, 2015
http://coastalenergyandenvironment.web.unc.edu/2015/07/26/azura-technology-captures-the-motion-of-the-ocean/

Energy Biz "Azura Powers Up" July 28, 2015
http://www.energybiz.com/article/15/07/wave-energy-test-rolling-forward-hawaii

Yale e360 "Will Tidal& Wave Power Ever Live Up to Their Potential" October 15, 2015
http://e360.yale.edu/mobile/feature.msp?id=2920

White House "Accelerating the Transition to Clean Energy" August 2015
https://www.whitehouse.gov/sites/default/files/accelerating_clean_energy.pdf

5. MODELING

Computer modeling of the Azura performance was not modelled as part of this project. However the data collected as part of this project was compared to a WEC-Sim computer simulation conducted as part of another program. A paper titled "WEC-Sim Model Validation of the Azura Prototype" was presented at the 2016 Marine Energy Technology Symposium in Washington, DC on April 26, 2016. The paper is available at the following site (username and password are both METS):

http://events.pennwell.com/nha2016/Public/Cust_DownloadHandout.aspx?Task=Speaker60970_Session15733_1.pdf