Open-Water Testing Plan for the WAV-WALL 2000*

Northwest National Marine Renewable Energy Center

Draft v1.1
July 1, 2013

** Fictitious representative wave energy conversion device*

Distribution

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Version

Date	Version	Name	Comments
7/11/2013	Draft V1.1	Driscoll and LiVecchi	Draft generated by NREL

Preface

This document is intended to be a guide to help develop test plans for wave energy conversion device testing at the NNMREC offshore testing site. It leverages testing guidelines and international standards from both the marine and hydrokinetic and wind energy fields, along with the NNMREC testing guidelines to develop a generic test plan.

The document is intended to reflect a real representative test plan in format and content. It is intended to encompass testing activities starting when the Wave Energy Converter (WECarrives at the mobilization site through sea testing and recovery. Specifications within this document are fabricated and should not be taken as a reference value or used in any way, other than to guide in the creation of a test plan. Also, this document details several tests that may be typical for an early stage WEC, but does not capture all possible testing needed to move a WEC through all stages of testing.

This test plan does not include critical supporting documents that are essential to carrying out a successful and safe open-ocean test. These include safety compliance and safe operating plans (for which examples and/or complete procedures can be obtained from NNMREC); a risk assessment; and mechanical and electrical drawings, which should be part of the WEC design and build package.

List of Acronyms and Abbreviations

CoG	center of gravity
CPU	central processing unit
DAS	data acquisition systems
DLC	design load cases
EtherCAT	Ethernet control automation technology
GMT	Greenwich Mean Time
GPS	global positioning system
GUI	graphical user interface
HMI	human-machine interface
IEC	International Electrotechnical Commission
I/O	input/output
Kg	kilogram
km^2	square-kilometer
kW	kilowatt
lb	pound
LED	light-emitting diode
mA	milliamp
MOIS	Modular Offshore Instrumentation System
MRU	Motion Reference Unit
NNMREC	Northwest National Marine Renewable Energy Center
NOMAD	Navy Oceanographic Meteorological Automatic Device
NREL	National Renewable Energy Laboratory
psi	pounds per square inch
PTO	power take-off

WEC	Wave Energy Converter
WET	Wave Energy Technologies

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1 Introduction and Background

Wave Energy Technologies (WET) and Oregon State University's Northwest National Marine Renewable Energy Canter (NNMREC) are working together to deploy and test the half-scale WAV-WALL 2000 wave energy converter offshore of Oregon. The WAV-WALL 2000 is an innovative new wave terminator technology that uses a flexible wall to extract energy from ocean surface waves. This is a floating system that self-orients itself into the prominent wave direction.

1.1 Testing Duration

Testing is expected to occur from July 1, 2013 to August 30, 2013.

1.2 Test Scope and Objectives

The operating principles and stability of the WAV-WALL 2000 have been proven through extensive wave basin testing at the Oregon State University (OSU) Hinsdale Wave Research Laboratory at scales up to 10:1. This year, WET has built a larger, half-scale 100-kilowatt (kW) testing and demonstration system for at sea testing. This WEC is a new build based on an innovative concept that integrates several systems for the first time. Therefore, an incremental testing strategy that prudently moves the technology from dockside testing to full open-ocean testing is specified within this document with the goal of minimizing risk and maximizing the probability of fully testing the system and providing a comprehensive data set to feed future designs. The objectives of the testing program are as follows:

Primary Objectives

- Perform dockside testing and sea trials to ensure the seaworthiness
- Conduct field demonstration, evaluation, and characterization of the WAV-WALL 2000 technology, including verification of safety, system function, integrity, and reliability
- Prove and demonstrate technology
- Establish power matrices
- Identify areas to improve performance and reliability while lowering cost.

Secondary Objectives

- Gain installation, operational, maintenance, and recovery experience
- Characterize and understand the environmental interactions and effects
- Collect data for numerical model calibration and validation
- Determine the skills, equipment, vessels, and procedures needed for installation, operation, maintenance, and recovery
- Develop and evaluate control strategies.

In Scope

The scope of this work includes:

- Characterizing the seaworthiness and seakeeping in various sea states via direction motion measurements
- Assessing deployment, operation, servicing, and recovery methods and procedures in real sea conditions of the WAV-WALL 2000 via deployment and testing at the NNMREC test site off of the Oregon coast
- Characterizing the safety, system function, integrity, and reliability, both dockside and at sea, for all expected device states and over a wide range of sea conditions by device state monitoring
- Evaluating power takeoff (PTO) function and performance over a range of sea conditions via direct power, sea condition, and PTO mechanical measurements
- Assessing the mooring configuration, stiffness, loads, and self-alignment tendency using motion measurements and mooring line tensions
- Collecting data to validate dynamics models, power generation predictions, and tune control algorithms
- Quantifying structural loads in response to sea conditions and device state and control.

Out of Scope

The following are considered out of scope:

- Assessing power quality to International Electrotechnical Commission (IEC) standards as the WEC will not be grid connected and no grid simulator is present
- Performing comprehensive environmental assessment of the WAV-WALL 2000.

1.3 Role and Responsibilities

WET will be the testing lead, and responsible for all logistics, as well as the schedule for transportation, assembly, installation, operation, and maintenance of the WAV-WALL 2000 WEC. WET will also be responsible for WEC monitoring, including all onboard sensors and data acquisition, as well as data quality control and distribution.

NNMREC will be solely responsible for the installation and operation of the Ocean Sentinel buoy and the TRIAXYS wave measurement buoy. NNMREC will be responsible for measuring the power at the load and the following metocean conditions: directional wave spectra and wind speed and velocity. The Ocean Sentinel buoy will also provide backup hotel power to WAV-WALL 2000.

Roles of Personnel

Person	Responsibility	Contact
John A. Doe	Testing manager—WET	555-555-1212
Sean Moran, OSU	Test site management and Ocean Sentinel buoy operations	
John B. Doe	WAV-WALL 2000 operations and maintenance	
John C. Doe	WAV-WALL 2000 sensors, data acquisition, and data quality	

2 References

2.1 Test Specific References

The following references are specific to the testing outlined within this document. These references provide critical information about the WEC, the Ocean Sentinel, and supporting systems that may be necessary for troubleshooting, verifying calibration, and determining accepted and safe operating requirements and methods.

1. NNMREC Safe Operating Procedure
2. Test Article Specifications: Mechanical
3. Test Article Specifications: Electrical
4. Interface Document
5. Test Article Deployment Plan
6. Test Article Operations and Maintenance Plan
7. Test Specific Instrumentation and Data Acquisition System.

2.2 General References

The following references were used to develop the testing plan:

8. Guidelines for Open-Water Testing of Wave Energy Converters (draft v0.3)
9. Overview and Bibliography of MHK Testing Guidelines and Relevant Standards.

3 Description of Test Articles, Apparatus, and Site

The overall at-sea testing consists of three distinct articles: 1) the WAV-WALL 2000 WEC, 2) the Ocean Sentinel buoy, and 3) a TRIAXYS wave buoy. The WEC uses a compliant three-leg mooring that constrains the horizontal motion to within a 30-meter (m) watch circle but allows the WEC to orientate itself normal to the predominate wave direction. The Ocean Sentinel uses a stiff three-leg mooring that constrains yaw and limits motion to about a 3-m watch circle.

The WEC and Ocean Sentinel are connected by an underwater cable with electrical conductors that transmit the power produced by the WEC to load banks aboard the Ocean Sentinel. The cable also contains fiber optic conductors to transmit data from the WEC to the data repository aboard the Ocean Sentinel, which are then relayed to shore via the Ocean Sentinel Radio Frequency communication system. The power cable lies on the ocean bottom and an inverse catenary (lazy wave) configuration is used at each end to connect to the buoys.

3.1 WAV-WALL 2000 WEC

The WAV-WALL 2000 is a wave terminator buoy that is designed to float and align itself with the predominant direction of oncoming waves. The buoy consists of an underwater structure that supports a large flexible buoyant “paddle” with its top about 3 m above the stillwater level. When operating, the paddle orientates itself perpendicular to the direction of wave travel and oscillates back and forth as waves pass. A direct drive generator is coupled to the paddle through a unidirectional magnetic drive unit that keeps the generator rotating in the same direction.

The WAV-WALL 2000 utilizes a three-leg compliant catenary mooring system that connects to a rotating bearing, allowing the WEC to align with oncoming waves. Each mooring leg consists of a 2,000 kilogram (kg) drag embedment anchor connected to 200 m of 2” chain. A clump weight is located at the connection point between the chain and 55 m of synthetic line that attaches to the fair leads on the WEC. The WEC has the following specifications.

Table 1. Summary of the WAV-WALL Technical Specifications

WEC Manufacturer and Contact Info	Wave Energy Technologies 8912 Ocean Tech Plaza Portland, OR 80345
Model	WAV-WALL 2000
Serial Number	2000-0001
WEC Type	Terminator
Mooring Type	Three-leg compliant catenary
Dimensions (feet)	15 m (length, perpendicular to the waves) x 2 m (width) x 20 m (height)
Height Above the Mean High Water Line (feet)	3 m
Net Weight, Including Ballast	32 tonnes
Reserve Buoyancy	3 tonnes
Rated Electrical Power (kW)	100 kW
Maximum Operating Sea State	7 on Beaufort Scale (5.5 m wave height)
Minimum Operating Sea State	2 on Beaufort Scale (0.5 m wave height)
Maximum Survival Sea State	10 on Beaufort Scale (12.5 m wave height)
Maximum Watch Circle	30 m
Controller	Bachmann M series
DAS	NREL MOISyT

The National Renewable Energy Laboratory's (NREL) Modular Offshore Instrumentation System (MOIS) is the data acquisition system that will be utilized on the WEC to provide the research measurements. The configuration of this system that will be utilized during testing is outlined in Reference 2. The channel list is outlined in Appendix 2.

3.1.1 Ocean Sentinel Buoy

The Ocean Sentinel is a surface buoy based on the 6-m Navy Oceanographic Meteorological Automatic Device (NOMAD) oceanographic buoy design. The Ocean Sentinel is equipped with a load bank to dissipate power from the WAV-WALL 2000 buoy, and with instrumentation to monitor and record performance and environmental data. It has aluminum hull with steel/aluminum/composite instruments (see Reference 2). The Ocean Sentinel is also outfitted with radio antennae, data acquisition systems (DAS), telemetry systems, monitoring devices (seabird detection, atmospheric monitors, cameras, etc.), and power systems (solar panels and diesel generator). The Ocean Sentinel instrumentation buoy will utilize a three-point mooring system that consists of three concrete block anchors positioned at points 120 degrees apart around a center position with a radius of approximately 100 m. The Ocean Sentinel will be tethered with polyester ropes to three subsurface floats, which will be attached with 1-inch stud link chain to their respective anchors on the seabed.

Table 2. Summary of the Ocean Sentinel Technical Specifications

Dimensions (feet)	6.5 m (21.25 ft) length x 3.2 m (10.5 t) width x 7.3 m (24 ft) height
Height Above the Mean High Water Line (feet)	4.5 m (15') (estimated to antenna locations above water surface)
Wet Mass of Buoy	9,000 kg (19,600 lbs) total weight, including fuel and equipment
Displacement Volume (%)	9,000 kg (19,600 lbs) (50%)

3.1.2 TRIAXYS Wave Measurement Buoy

The TRIAXYS wave measurement buoy is deployed to measure and record the wave directional spectra and other wave statistics. It is constructed of stainless steel and polycarbonate, and it is approximately 1 m in diameter and approximately 70 kg. Wave data recorded by the TRIAXYS wave measurement buoy will be transmitted via wireless telemetry to the Ocean Sentinel buoy or directly to shore.

Table 3. Summary of the TRIAXYS Wave Buoy Technical Specifications

Dimensions (feet)	1 m diameter x 1 m high
Height Above the Mean High Water Line (feet)	0.5 m
Wet Mass of Buoy	200 kg, including batteries
Displacement Volume (%)	200 kg (50%)

4 Testing Site and Test Setup

4.1 Staging Area

The staging area will be at the Port of Toledo boatyard at Sturgeon Bend:

Port of Toledo Boatyard
1000 Altree Lane
Toledo, Oregon 97391
541-336-0333
boatyard@portoftoledo.org

The staging area is about 10 miles upriver from the river's mouth at Newport, where it is a 20 mile transit to the deployment site. The WAV-WALL 2000 and the Ocean Sentinel buoys will be assembled and dry tested at the port. Upon a successful test readiness review and verification, the buoys will be towed to Newport where they will begin the first stages of ocean testing.

4.2 Test Site

For this project, the WAV-WALL 2000, the Ocean Sentinel instrumentation buoy, and a TRIAXYIS wave measurement buoy will be deployed in an open-water setting to perform off-grid testing. The project site is located within a 3.4-square kilometer (1-square nautical mile) area in the Pacific Ocean, approximately 3 kilometers (2 miles) off the coast of Oregon near the city of Newport. The closest harbor is Newport, which is located approximately 4 miles (as the crow flies) away, or about 6 nautical miles by boat. The water depth is approximately 45 m [180 feet (ft)]; the location features exposure to unobstructed ocean waves with high energy resources; comparatively low levels of marine traffic but highly visible to marine navigation; proximity to a port for device deployment, maintenance, and recovery (if needed). It is also sufficiently distant from the Yaquina River mouth to avoid hydraulic sediment transport or other technical issues related to proximity to the river, and out of the direct westerly line of sight from Yaquina Head to avoid aesthetic impacts.

The Ocean Sentinel is located about 400 m to the northeast of the WEC and is facing northwest, into the prevalent direction of wave propagation—from the northwest to the southeast. The TRIAXYS wave buoy is situated about 200 m in front of the WEC in the northwest direction. The maximum footprint of the Ocean Sentinel and TRIAXYS wave monitoring buoy and their mooring systems is 240 m x 190 m (800 ft x 625 ft). The footprint of the WAV-WALL 200 device and its mooring system is 300 m x 300 m (1000 ft x 1000 ft). The coordinates marking the overall project area and deployment site are shown in Table 4.

Table 4. Geodetic Coordinates of the Testing Range and of the Deployment Site for the Test

Description	Latitude	Longitude
Northwest Overall Corner	N44.697824449	W124.146230421
Northeast Overall Corner	N44.698573997	W124.122886145
Southeast Overall Corner	N44.681923759	W124.121838910
Southwest Overall Corner	N44.681174427	W124.145176456
Northwest Site Corner	N44.69654918	W124.12980796
Northeast Site Corner	N44.69481186	W124.12777619
Southeast Site Corner	N44.69444426	W124.12518974
Southwest Site Corner	N44.69430052	W124.12966653

Table 5. Geodetic Coordinates of the Mean Location of the WAV-WALL, Ocean Sentinel, and the TRIAXYS Buoys

Description	Latitude	Longitude
WAV-WALL 2000	N44.69503362	W124.12779014
Ocean Sentinel	N44.69573186	W124.12655239
TRIAXYS Buoy	N44.69524106	W124.12844402

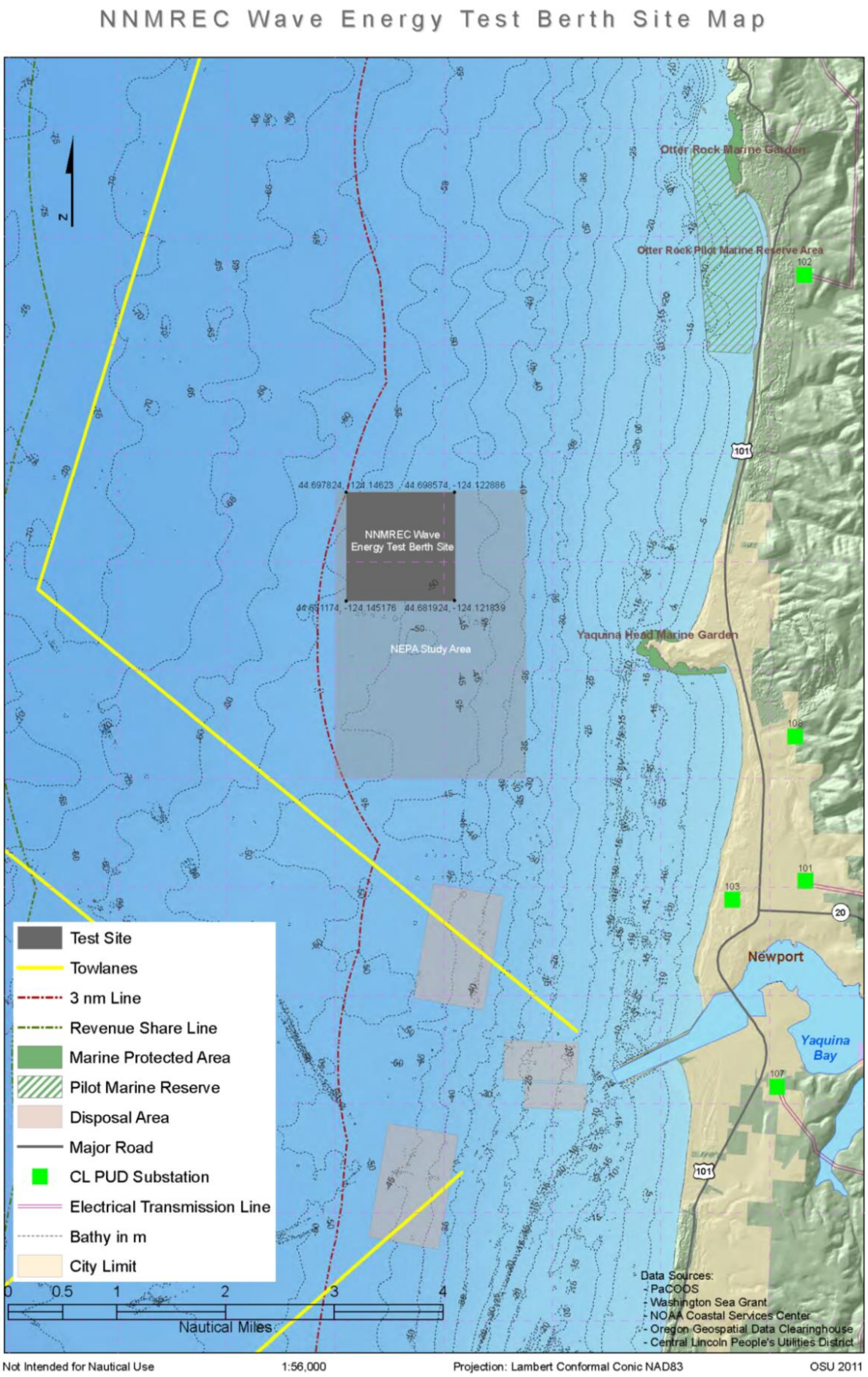


Figure 1. NNMREC offshore testing site

Source: NNMREC

4.3 Site Calibration and Valid Measurement Sectors

As previously mentioned, the project site is located within a 3.4-square kilometer (1-square nautical mile) area in the Pacific Ocean, approximately 3 kilometers (2 miles) off the coast of Oregon near the city of Newport. The coastline runs predominately straight north-south with only small extrusions seaward. Based on this topography, the incoming waves are considered valid when traveling between 200° and 340° of true north.

NNMREC has conducted an extensive site characterization campaign, and this included deploying two wave buoys. One was placed at the WEC deployment location and the other at the site of the TRIAXYS buoy. Simultaneously, wave characteristics, the current profile, and meteorological conditions (wind speed and direction) were measured to characterize their influences on the wave climate for a period of one year. NNRMEC concluded that, within the valid range of wave propagation direction, there is no difference between the wave field at the measurement site and at the WEC deployment location.

During the test period, from July 1 to August 30, 2013, another WEC will be tested at the NNMREC testing site (see Figure 2). This WEC will be located approximately 400 m to the southwest of the WAV-WALL 2000 at a bearing of 230°, and it will block waves traveling from that direction. The Ocean Sentinel buoy is at a bearing of 320° and will block waves traveling from that direction toward the WAV-WALL 2000. The TRIAXYS buoy is located forward of both WECs undergoing testing, and waves traveling to the buoy from between 200° and 340° of true north are not obstructed. Therefore, all wave measurements between 200° and 340° of true north are considered valid.

Therefore, considering the incoming waves are considered valid when traveling between 200° and 340° of true north, and excluding the sectors where the waves are affected by the Ocean Sentinel and the other WEC, the valid measurement sectors are:

Table 6. Valid Wave Measurement Sectors[a]

Valid Measurement Sector	Direction
A	325°-340°
B	235°-315°
C	200°-225°

[a] All data outside of these sectors will not be used.

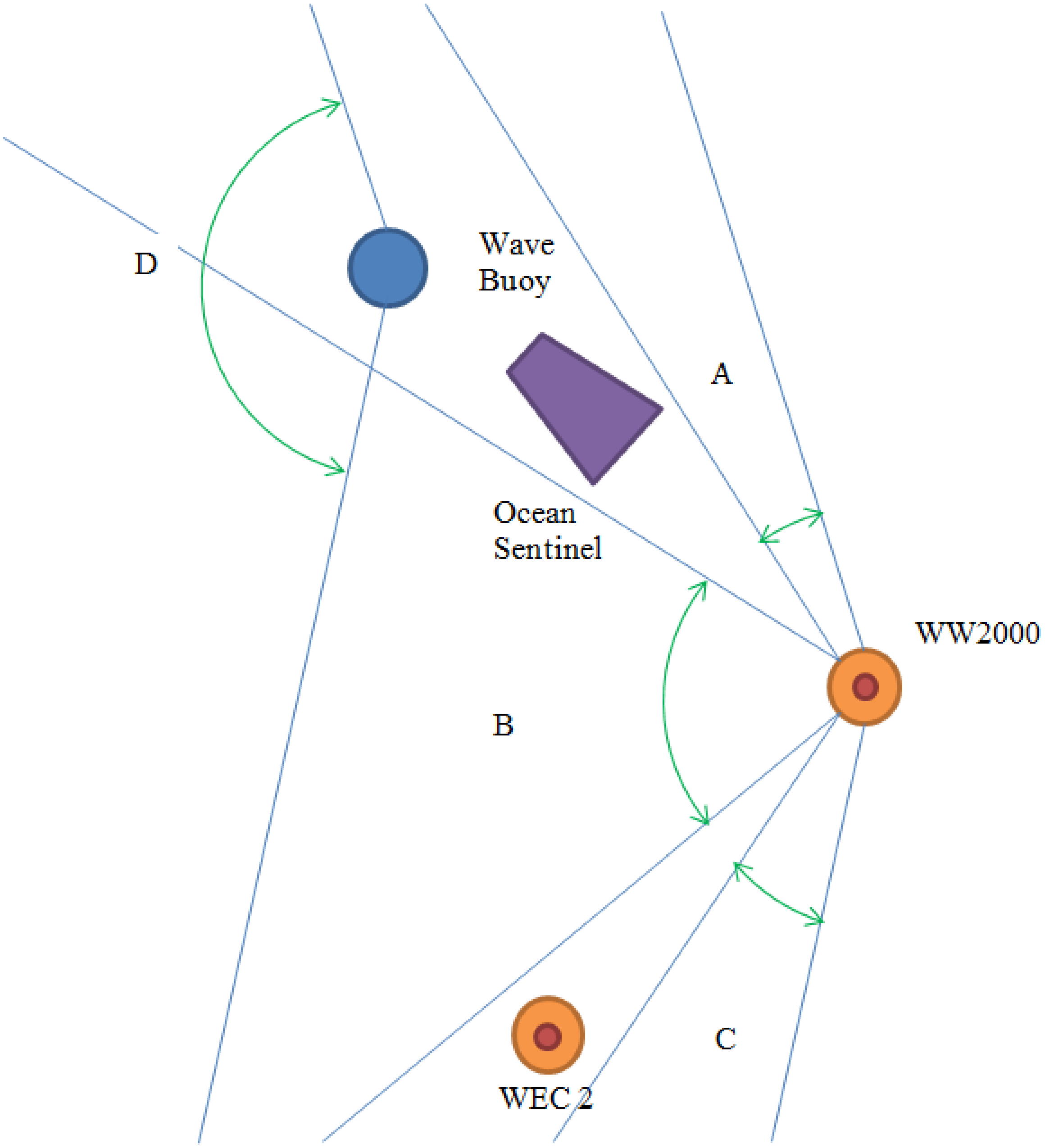


Figure 2. Diagram of the buoy positions and valid measurement sectors within the test site

Source: NNMREC

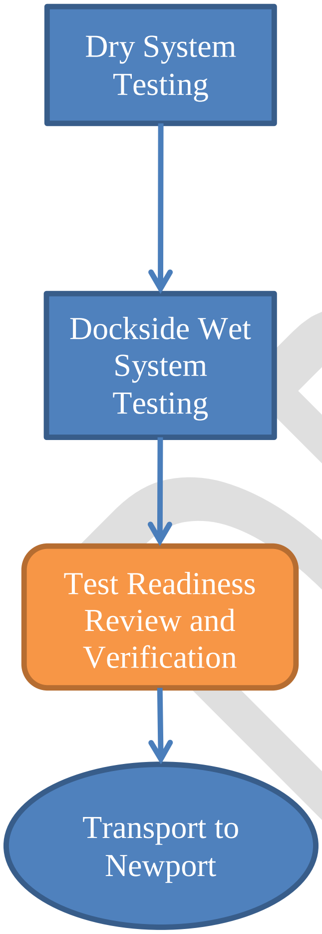
5 Testing Overview and Methodology

Testing of the WAV-WALL 2000 will closely follow the testing methodology outlined in the Guidelines for Open-Water Testing of Wave Energy Converters (see Reference 8 in Section 2) to minimize project/testing risk and lead to a comprehensive set of quality data. Therefore, two primary stages will be followed: 1) predeployment testing and readiness verification and 2) open-water testing.

5.1 Predeployment Testing and Readiness Verification Overview

The first stage of testing will involve the following incremental testing steps (the buoy will be delivered fully assembled with all components individually tested at the assembly yard prior to transport to the staging area):

Table 7. Predeployment Tests[a]



Prior to placing the system in the water, a set of comprehensive tests will be conducted to verify the system is ready to get wet. These tests include:

1) Safety and Function (a.1-3)
2) System Integrity (b.1)
3) Stability and Seakeeping (c.1)
4) Sensors (d.1 and d.2)
5) Health and Condition (g.1).

A short-duration wet test will be conducted to further verify seal integrity and overall sensor and electronic operation. This will be done dockside with the WEC floating somewhat horizontally, but ballasted so all watertight compartments are underwater. The tests that will be conducted are:

1) System Integrity (b.1)
2) Sensors (d.1 and d.2).

Before proceeding to towing the buoys to Newport in preparation for open-water testing, a test readiness review and verification will be conducted. The review will include a review of previous testing results and verification that all previous deficiencies have been corrected. It will also review the open-water testing plan and all safe operating procedures. Both WET and NNMREC will participate in the review.

[a] Tests identified within this table are specified per Section 1.3.3 in NNMREC's Guidelines for Open-Water Testing of Wave Energy Converters.

5.2 Open-Water Testing Overview

The second stage testing will also involve an incremental testing procedure to reduce risk before the WAV-WALL 2000 is deployed for long duration testing and to provide a high degree of confidence in the survival and operation of the complete system for open-water testing. For this initial deployment, the aim is to test the system in operating sea states while avoiding extreme seas that will exceed system operation. Testing in larger seas will be the aim of future tests once confidence is gained in system operation and survivability.

Table 8. Open-Water Tests

Initial Sea Trials	Prior to placing the system on moor where recovery can be difficult, the WEC will be deployed in the open-ocean under calm sea conditions without the aid of a mooring. The goal is to perform a comprehensive test of function and stability, as outlined in Reference 8 and replicated in Figure 3, with the ability to easily recover for adjustments and fixes. Test duration is expected to be one to four days. Tests include: 1) System Integrity (b.1) 2) Stability and Seakeeping (c.1 and 4) 3) Sensors (d.1and 2). The system will not be operated to produce power during this phase.
↓ Short Duration Testing	Once the WEC is operating properly, the WEC will be moored at the testing location for a period of 14-21 days, after which it will be recovered for inspection. Tests and monitoring include: 1) Stability and Seakeeping (c.3 & 4) 2) Power Performance (i.1) 3) Loads, Response, Wear, and Fatigue (j.1-3) Once recovered, the WEC will be given a thorough inspection to look for any failures, leaks, corrosion, or wear that needs to be mitigated before long-duration testing.
↓ Long Duration Testing and Tuning	The WEC will be redeployed to the mooring site after all issues identified in the short-duration testing have been corrected. The same testing will be conducted as in the short-duration testing but with the aim of collecting longer-term data sets and filling up all test matrices.

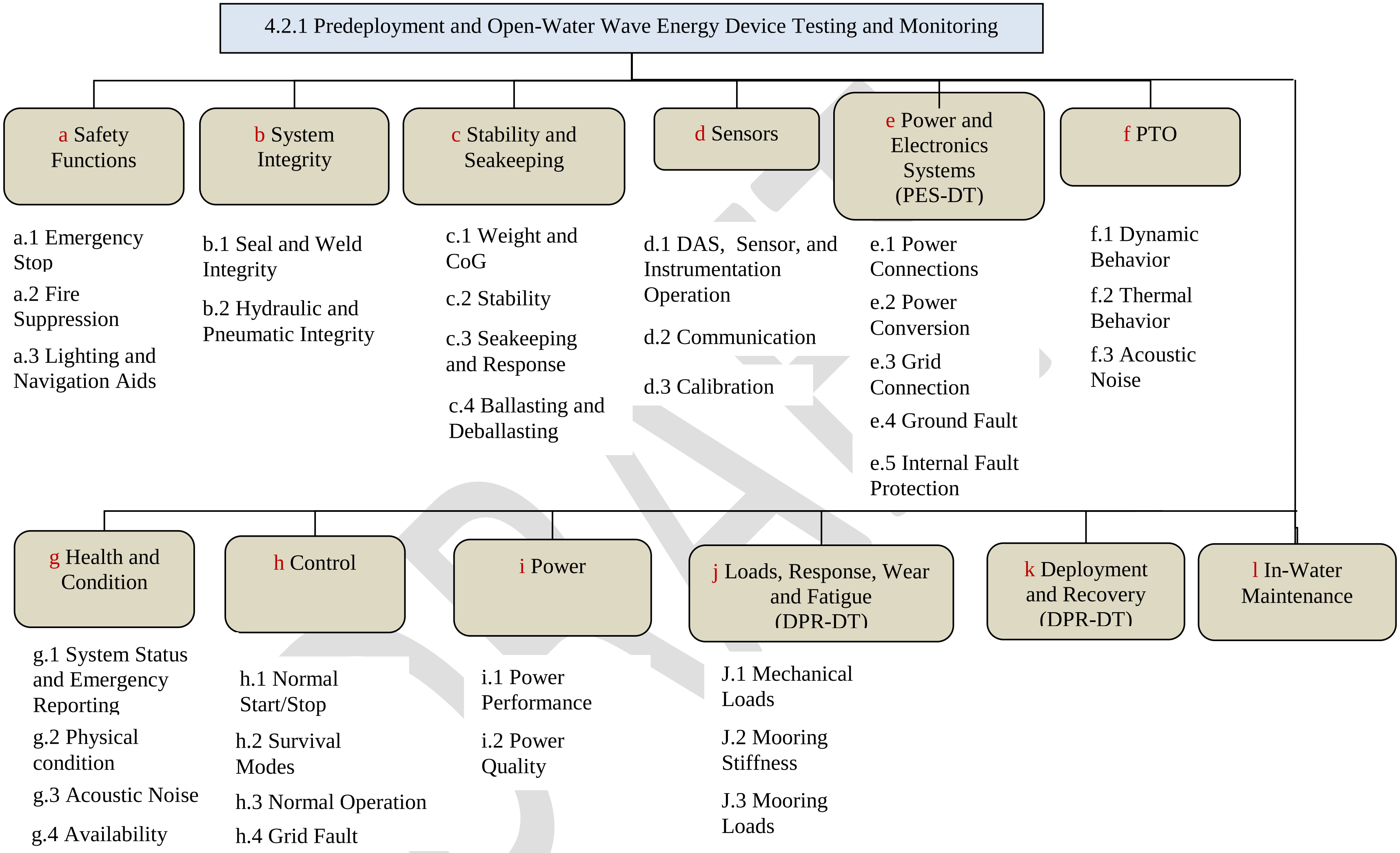


Figure 3. Predeployment and open-water wave energy device testing and monitoring[1]

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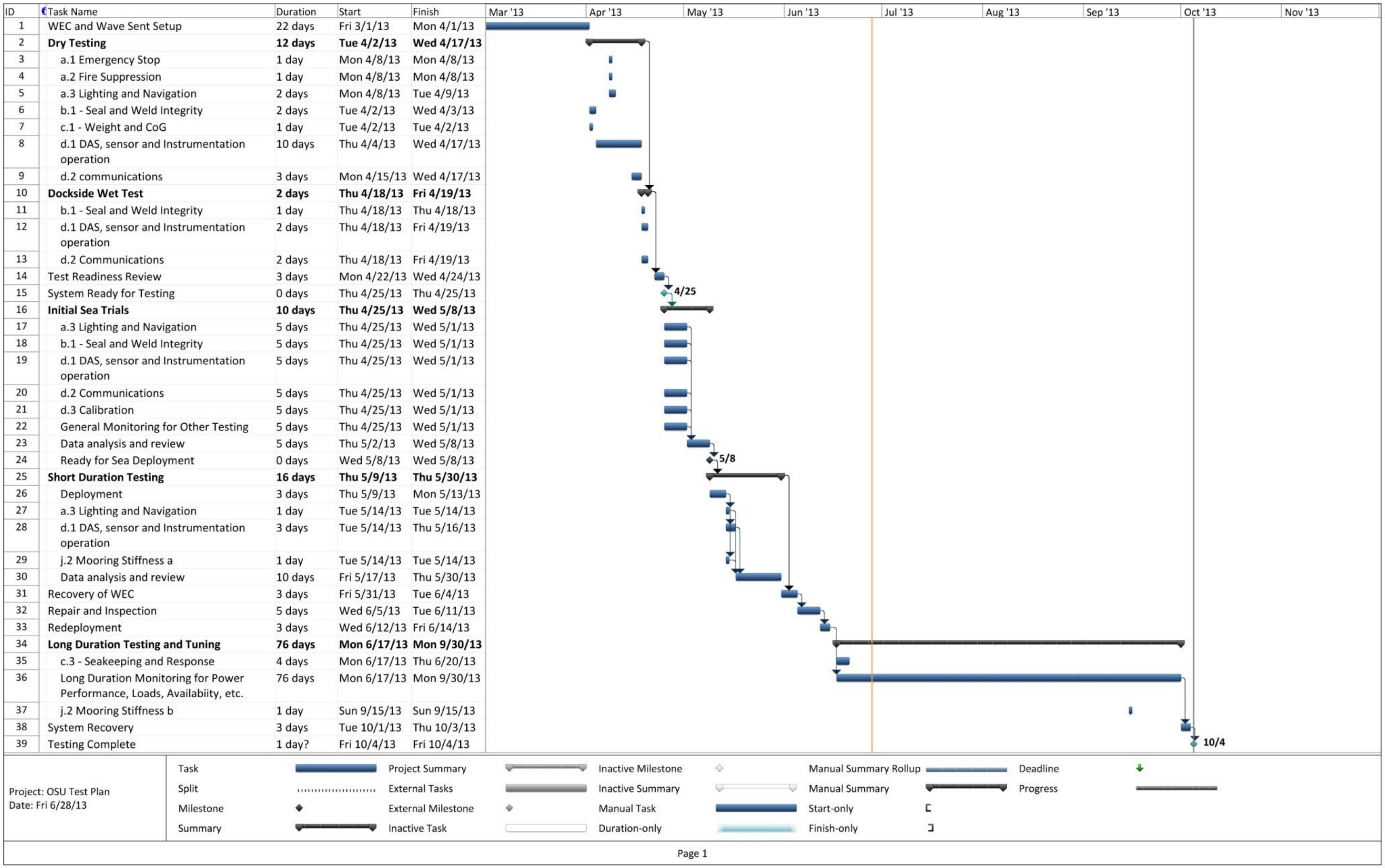
[1] Information from Reference 1 in Section 2 (Guidelines for Open-Water Testing of Wave Energy Converters).

5.3 Testing Schedule



ID	Task Name	Duration	Start	Finish
1	WEC and Wave Sent Setup	22 days	Fri 3/1/13	Mon 4/1/13
2	**Dry Testing**	**12 days**	**Tue 4/2/13**	**Wed 4/17/13**
3	a.1 Emergency Stop	1 day	Mon 4/8/13	Mon 4/8/13
4	a.2 Fire Suppression	1 day	Mon 4/8/13	Mon 4/8/13
5	a.3 Lighting and Navigation	2 days	Mon 4/8/13	Tue 4/9/13
6	b.1 - Seal and Weld Integrity	2 days	Tue 4/2/13	Wed 4/3/13
7	c.1 - Weight and CoG	1 day	Tue 4/2/13	Tue 4/2/13
8	d.1 DAS, sensor and Instrumentation operation	10 days	Thu 4/4/13	Wed 4/17/13
9	d.2 communications	3 days	Mon 4/15/13	Wed 4/17/13
10	**Dockside Wet Test**	**2 days**	**Thu 4/18/13**	**Fri 4/19/13**
11	b.1 - Seal and Weld Integrity	1 day	Thu 4/18/13	Thu 4/18/13
12	d.1 DAS, sensor and Instrumentation operation	2 days	Thu 4/18/13	Fri 4/19/13
13	d.2 Communications	2 days	Thu 4/18/13	Fri 4/19/13
14	Test Readiness Review	3 days	Mon 4/22/13	Wed 4/24/13
15	System Ready for Testing	0 days	Thu 4/25/13	Thu 4/25/13
16	**Initial Sea Trials**	**10 days**	**Thu 4/25/13**	**Wed 5/8/13**
17	a.3 Lighting and Navigation	5 days	Thu 4/25/13	Wed 5/1/13
18	b.1 - Seal and Weld Integrity	5 days	Thu 4/25/13	Wed 5/1/13
19	d.1 DAS, sensor and Instrumentation operation	5 days	Thu 4/25/13	Wed 5/1/13
20	d.2 Communications	5 days	Thu 4/25/13	Wed 5/1/13
21	d.3 Calibration	5 days	Thu 4/25/13	Wed 5/1/13
22	General Monitoring for Other Testing	5 days	Thu 4/25/13	Wed 5/1/13
23	Data analysis and review	5 days	Thu 5/2/13	Wed 5/8/13
24	Ready for Sea Deployment	0 days	Wed 5/8/13	Wed 5/8/13
25	**Short Duration Testing**	**16 days**	**Thu 5/9/13**	**Thu 5/30/13**
26	Deployment	3 days	Thu 5/9/13	Mon 5/13/13
27	a.3 Lighting and Navigation	1 day	Tue 5/14/13	Tue 5/14/13
28	d.1 DAS, sensor and Instrumentation operation	3 days	Tue 5/14/13	Thu 5/16/13
29	j.2 Mooring Stiffness a	1 day	Tue 5/14/13	Tue 5/14/13
30	Data analysis and review	10 days	Fri 5/17/13	Thu 5/30/13
31	Recovery of WEC	3 days	Fri 5/31/13	Tue 6/4/13
32	Repair and Inspection	5 days	Wed 6/5/13	Tue 6/11/13
33	Redeployment	3 days	Wed 6/12/13	Fri 6/14/13
34	**Long Duration Testing and Tuning**	**76 days**	**Mon 6/17/13**	**Mon 9/30/13**
35	c.3 - Seakeeping and Response	4 days	Mon 6/17/13	Thu 6/20/13
36	Long Duration Monitoring for Power Performance, Loads, Availabiity, etc.	76 days	Mon 6/17/13	Mon 9/30/13
37	j.2 Mooring Stiffness b	1 day	Sun 9/15/13	Sun 9/15/13
38	System Recovery	3 days	Tue 10/1/13	Thu 10/3/13
39	Testing Complete	1 day?	Fri 10/4/13	Fri 10/4/13

Project: OSU Test Plan
Date: Fri 6/28/13

6 Predeployment Testing

6.1 Dry System Testing

The following tests shall be performed with the WEC fully assembled and on the dock. The WEC shall not be placed in the water until all of these tests are successful.

6.1.1 Safety Functions: a.1 Emergency Stop (and Remote Normal Stop)

The goal of this test is to verify the two emergency stop buttons and the software actuated stops function as specified.

State of WEC: For each test, the controller is in operating mode—waiting for waves, paddle is unlocked, and the mechanical brake is disengaged. The human-machine interface (HMI) is connected to the DAS and receiving real time updates that are displayed on the graphical user interface (GUI) system status and function screen.

Verification of Stop Button Function

Methodology: Ensure the WEC and the HMI are in the correct states before proceeding. Visually inspect the paddle lock and brake to ensure they are disengaged. Then perform each of the following steps for each of the stop buttons.

1. Press the stop button.
2. Verify the mechanical brake engages (this can be seen by observing the brake linkage between the actuator and brake).
3. Verify the WEC controller is switched to nonoperating-locked down state.
4. Verify the WEC lock is engaged.

Verification of Remote Normal Stop Function

Methodology: Ensure the WEC and the HMI are in the correct states before proceeding. Visually inspect the paddle lock and brake to ensure they are disengaged. Then perform each of the following steps for each of the stop buttons. Note that there are two stopped states: nonoperating-stopped paddle-free and nonoperating-stopped locked down. This test will verify the stopped locked down function.

1. On the GUI system status and function screen, press the stop and lockdown button.
2. Verify the mechanical brake engages (this can be seen by observing the brake linkage between the actuator and brake).
3. Verify the WEC controller is switched to nonoperating-stopped locked down.
4. Verify the WEC lock is engaged.

Pass Criteria: All safety stops engage the mechanical break and paddle lock, and the controller is switched to the nonoperating-stopped locked down state.

6.1.2 Safety Functions: a.2: Fire Suppression

The purpose of this test is to verify the readiness of the fire suppression system and the ability to remotely actuate it.

State of WEC: It is essential the halon controller is placed in the test state. Do not proceed until this is certain. Also, ensure that no one is within 10 m of the buoy.

Methodology: Before starting, verify the pressure in each of the halon tanks is sufficient—the needle on the pressure gauge should be in the green. Also, verify the halon controller has a flashing green light, which indicates it is in an operating state.

1. Confirm no one is within 10 m of the buoy and that one person, not the person conducting the test, is controlling the area to ensure no one enters. Use yellow caution tape to seal the area off.

2. On the GUI system status and function screen, press the activate fire suppression, and then click yes. Carefully watch and listen to see if the halon system activates—it will be obvious because a high volume sound and large white cloud will be produced.

3. Verify the halon controller has switched to activate—a flashing red light and audible alarm will be produced. If the controller does not switch to activation state, the test will be considered a failure.

4. Reset the halon controller and switch it to operation.

Pass Criteria: The halon controller switches to activate its “activate state”.

6.1.3 Safety Functions: a.3 Lighting and Navigation Aids

The purpose of these tests is to verify the function of the navigation lighting on the WEC. The navigation light is a fully sealed, omnidirectional solar-powered light-emitting diode lantern.

Methodology:

1. Prior to install (if installed, remove the light for the following tests), the light will be turned and the flash pattern will be verified to be one yellow flash every four seconds (15 flashes per minute).

2. The light is equipped with a light sensor to switch the lantern on and off. Switch the lantern to operate, then place the lantern in a dark area to verify the light automatically switches on and has the correct flash timing, then take it to a light area and verify it automatically switches off.

3. Submerge the lantern to a depth of 3 m and hold it there for two hours. If the light does not function or if any condensation or evidence of water ingress is evident, the test will be considered a failure.

4. Leave the lantern in the sun for 8 hours to charge. Then place in a dark area for 48 hours to verify long-term operation.

5. Install the lantern, and every day until deployment, check the lantern to make sure it is off in daylight, then cover to verify that it turns on. If the light does not turn on, the test will be considered a failure.

Pass Criteria: The light passes all the previous tests and reliably turns on and off.

6.1.4 System Integrity: b.1 Seal and Weld Integrity

The WEC consists of four watertight compartments, along with an external housing for some instrumentation. To ensure the buoy does not take on water during deployment and to reduce the risk of damage to dry components to even small leaks, all compartments will be tested and inspected prior to moving toward a wet test.

Pressure Testing

Each and every compartment or housing of the WEC will be subjected to separate, nonsimultaneous air tests at distinct times to verify water tightness according to the air test specified in Section 4.5.2 of the specifications of the U.S. Coast Guard for fabrication of steel ocean buoys (specification No. 464, Revision J). To do this, each chamber will be pressured to 3 pounds per square inch (psi) above ambient and the air source turned off. Internal pressure will be recorded every minute for ten minutes to a resolution of 0.1 psi, using a Fluke-719 30G as detailed in Appendix 1. Simultaneously with the pressure testing, a soap water solution will be applied to all welds and seals. The test shall be done when the WEC is not in direct sunlight and when the outside air temperature is constant.

Pass Criteria: No drop in pressure or leaks detected with the soapy water (via manifestation of bubbles).

Table 9. Capture Matrix for Pressure Testing

Time (min)	Pressure Reading in Each Chamber (psi)				
	1	2	3	4	Inst. Housing
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
Bubbles (Y/N)					

Weld Inspection: While the welds have been subject to visual and non-destructive inspection during fabrication and assembly, the goal is to perform a final visual inspection of all welds to identify any damage or defect that may have manifested during transport. The inspection shall look for obvious damage to welds or weld failure, but also keep an eye out for welding discontinuities, undersized welds, undercut, overlap, surface cracking, surface porosity, under fill, incomplete root penetration, excessive root penetration, burn through, and excessive reinforcement. Be sure to keep notes on the inspection.

Pass Criteria: No defects in the welds exist.

6.1.5 Stability and Seakeeping: c.1 Weight and CoG

The goal is to compare the as-built weight and CoG with those estimated from design and from the weight tracking spreadsheet that was used to capture as-built weights of the WEC components.

State of WEC: Nonoperating with paddle locked in the home position.

Instruments: Four load cells, one in each lifting line, rated at 16 tonnes each with a resolution of 10 N. The load cells shall be calibrated before and after lift using 5,000 and 10,000-lb calibration weights.

Setup: The WEC has four lift points centered on the CoG that allows the WEC to be lifted horizontally. A 12-m lifting line will be connected to each lifting point and connected to a common shackle. Each lifting line will make a 45° angle with the horizontal and support a load of 11.3 tonnes (approximately 25,000 N).

Methodology: Slowly bring tension into each of the lines and gradually increase load until the WEC is lifted and fully clear of the ground. Record the tension in each load cell, and the angle of each line and of the WEC at the horizontal alignment plate with a digital inclinometer. Lower the WEC to the ground and unload lifting lines. Switch lifting lines and repeat two more times. Line 1 is attached to lifting point 1 – marked on the buoy and identified in platform drawing four in the WAV-WALL 2000 drawing booklet.

Table 10. Capture Matrix for the Weight and CoG Measurements

	Lift 1	Lift 2	Lift 3
Line 1 Angle			
Line 1 Tension			
Line 1 Angle			
Line 1 Tension			
Line 1 Angle			
Line 1 Tension			
Line 1 Angle			
Line 1 Tension			
WEC Angle			

6.1.6 Sensors: d.1 DAS, Sensor and Instrumentation Operation

After the system is fully assembled and the instruments and DAS are installed and connected, this testing shall be conducted to verify the complete operation of the instrumentation suite. Testing is divided into three parts, 1) the system test, 2) the individual channel test, and 3) duration testing. Clearly document the results of each of the steps in the following methodologies.

Setup: All sensors installed on the WAV-WALL 2000 and connected to the DAS. The mooring load cells, while not installed on the mooring lines, shall be plugged into the connectors that will be used during deployment.

System Test

This test aims to verify that the DAS is operating and the base functions are working correctly. This set of tests need to be conducted first to catch any component failures that may be harder to detect in the following tests.

Methodology:

1. Turn on DAS, but do not start the acquisition software. If possible, monitor current and voltage to identify any shorts or excessive power draws. Compare the power load on the DAS to that of bench testing. This should be done for about 10 minutes.

	Bench Test Power Draw	Field Power Draw
DAS—Central Chassis	15 W	
DAS—Remote Chassis	8 W	

2. For each instrument that is connected at the time of this test, turn these on one at a time, and monitor current and voltage to identify any shorts or excessive power draws.

	Bench Test Power Draw	Field Power Draw
DMS	20 W	
VT 101 GPS	10 W	
Altimeter	5 W	

3. Start the DAS software and begin to collect data; if possible, monitor the central processing unit load and compare with values from bench testing.

	Bench Test Power Draw	Field Power Draw
DAS—Central Chassis	25 W	
DAS—Remote Chassis	18 W	

4. The global positioning system (GPS) time is displayed on the GUI on the HMI computer connected to the DAS. To verify the DAS time is correct against reference GPS, check Greenwich Mean Time (GMT), not local time.
5. Using the file transfer protocol software, go onto the DAS hard drive and verify data files are being recorded with the correct naming scheme. For each file, check that the file exists and then check the file size every minute to verify that the file is being written to.

IP address: 152.152.152.3
User: NNMREC_test
Password:1234

6. Turn on the Bachmann controller and start it. Once it is fully up (about one minute), verify the load and compare with values from bench testing. Then verify the DAS is reading data via the GUI on the HMI computer; ensure that the Bachmann time and channels are being updated.

	Bench Test Power Draw	Field Power Draw
Bachmann Controller	25 W	

Pass Criteria: All values of power usage match bench test values, all data files are being written and updated, and the Bachmann controller data is being passed to the DAS.

Individual Channel Test

The operation of each of the channels and associated instruments were verified and calibrated before deployment. This test aims to verify that channels were connected correctly when installed on the WEC and that no obvious damage to the instruments has occurred via reasonable channel readings.

Methodology: For each sensor or group of sensors, perform the following steps:

1. Turn the sensor/instrument on and if possible, monitor current and voltage in each component to identify any shorts or excessive power draws.
2. Verify via the GUI on the HMI computer that the data channel(s) are being updated and has a representative value.
3. Open the data file and verify that data for the channel(s) are being written.
4. For the following sensors, perform the following actions to initiate a change in state and then verify the change on the HMI GUI:

Sensor	**Action**
Water Ingress in Compartments 1-4	Separately, short the water ingress sensor with a section of copper wire
Temperature sensor in Compartments 1-4	Separately, apply an activated self-heating hand warmer to each thermistor
DMS MRU	Unbolt the MRU, and translate and rotate the unit, then reattach in the original configuration

Once all channel performance and data recording has been verified, at least two hours of data shall be recorded for all channels. Then this data shall be used with the NREL_channel_check software to quickly verify all channels and that those are being recorded in value, sample rate, time stamp, etc., and that each file is being properly incremented each hour. For serial channels that are not parsed and converted into floating point or equivalent representations, check the strings to make sure they are properly populated and the timing between strings is correct.

Pass Criteria: All channels are being read by the DAS, and correctly updated and recorded. All data files are being updated properly each hour.

Duration Testing

After the system test and individual channel test, the DAS will be run continuously for at least seven days to check for any issues with stability, sensor heating, and other items that may cause DAS/sensor failure. Each day, one hour of data will be checked with the NREL_channel_check software to verity the system and individual channels are still operating correctly.

Pass Criteria: The DAS operates for the entire period without error or fault. All data files are being updated properly each hour and each day.

6.1.7 Sensors: d.2 Communication

Communication between the WAV-WALL 2000 and the shore side interface computer will be via the cellular connection on the Ocean Sentinel buoy and directed through the umbilical between the buoys. *This will be the first time the WEC and Ocean Sentinel systems will be connected*. This test will verify the systems are able to remotely:

- Communicate with the WEC and verify WEC status
- Receive WEC status updates and emergency notifications
- Reconfigure the DAS, reboot the DAS, and reinstall the operating system
- Turn on and off power to the DAS and various sensors
- Download data.

Setup: The umbilical between the WAV-WALL 2000 and the Ocean Sentinel must be connected, and the Ocean Sentinel must but turned on and connected to the local cellular service.

Methodology:

1. Ensure the WEC and Ocean Sentinel DAS and communication systems are turned on. Individually ping the Ocean Sentinel router and the MOIS DAS from the Human-Machine-Interface (HMI) computer. Record the cellular signal strength on both the HMI and Ocean Sentinel, the round trip time, and the number of lost packets. Using the GUI on the HMI, verify the correct WEC status is being displayed.
    - Ocean Sentinel router IP address: 152.152.152.1
    - WAV-WALL DAS IP address: 152.152.152.3.
2. Using the HMI, remotely 1) shut down the DAS, 2) start up the DAS, and 3) reboot the DAS.

3. A WEC status is sent every 15 minutes to test_status@WaveEnergyTech.com. Leave the system operating until at least two status messages are received. As part of the safety and function tests, faults will be introduced to test the emergency notifications system. Be sure the communication (WEC-Ocean Sentinel-HMI) remains connected to support this test.

4. Turn on the DAS and let it run for two hours, then FTP into the storage location. Perform the following tasks: 1) download the data, 2) clear the data and 3) verify new data is being written.

5. Using the remote power control features in the GUI on the HMI, individually power down and power up each of the instruments and the DAS. Start with the DMS Inertial Motion Unit (IMU), which is the first choice, and work down the list.

Additionally, the DAS aboard the WEC utilizes separate satellite and WiFi connections to facilitate communication between the DAS and HMI when the Ocean Sentinel buoy is not connected or nonoperational. **Separately, for each of these systems, communication will be established with the HMI, and the previous communication steps will be repeated.**

6.1.8 Health and Condition: System Status and Emergency Reporting

The aim of this test is to verify the performance of the WEC's automatic status and emergency reporting system by simulating faults.

Setup: The umbilical between the WAV-WALL 2000 and the Ocean Sentinel must be connected, and the Ocean Sentinel must but turned on and connected to the local cellular service. This needs to be performed after 6.1.7, which is when the system status testing was performed.

Methodology:

1. Ensure the WEC and Ocean Sentinel DAS and communication systems are turned on. Individually ping the Ocean Sentinel router and the MOIS DAS from the HMI computer.
2. Individually perform the follow fault simulations:

Fault	Method to Simulate
Water Ingress	In compartment 3, short the water ingress sensor with a section of copper wire
Generator temperature	Unplug the generator temperature probe and connect the 15 mA source
Mooring line load cell	Unplug the load cell and connect the shut to simulate full load
GPS	Turn off the GPS

3. For each of these faults, an immediate status alert should be sent to test_status@WaveEnergyTech.com and forwarded to each of the test leads. Record the message received, and the time between fault occurrence and receipt of the message.

6.2 Dockside Wet Test

For this test, the WEC shall be lifted and placed in the water dockside. It shall be ballasted so all underwater compartments are, to the greatest degree possible, underwater. The test duration shall be 48 hours, during which time, the following tests will be conducted and the buoy will not be removed:

- System Integrity: b.1 Seal and Weld Integrity
- Sensors: d.1 DAS, Sensor and Instrumentation Operation

6.2.1 System Integrity: b.1 Seal and Weld Integrity

The purpose of this test is to detect any water leakage. Each of the four water ingress and pressure sensors will be monitored for the entire 48 hours. Any water leakage into any one of the compartments will be considered a failure.

6.2.2 Sensors: d.1 DAS, Sensor, and Instrumentation Operation

The purpose of this test is to detect any water-related malfunctions of the DAS; it is not intended to repeat the entire testing of 6.1.6. Therefore, only a subset of the sensor and instrumentation operation shall be performed. The tests to be repeated are:

- System Tests: 1, 2, and 3
- Individual Channel Tests: 1 and 2.

6.2.3 Sensors: d.2 Communication

The purpose of this test is to verify the communication with the WiFi, which will be used for the initial sea trials when the WEC is in the water. The following tests to be repeated, but only for the WiFi, are 1, 2, and 5 of the methodology of test 6.1.7.

7 Open-Water Testing

7.1 Initial Sea Trials

The purpose of the initial sea trials is to verify the stability and some system function, prior to hooking up to the mooring and while the WEC is still easy to recover. For this test, the WEC will be towed out to a water depth of at least 50 m. Once on station, it will be ballasted to its vertical position and tested. Once the test is complete, the WEC will be deballasted to the horizontal position and towed back to dock. **During the test, a tow line shall remain attached to the WEC at all times.**

Maximum Sea State: The initial sea trials test shall be performed during relatively calm conditions (less that Sea State 3) to limit the danger of recovery.

7.1.1 System Integrity: b.1 Seal and Weld Integrity

The purpose of this test is to detect any water leakage. Each of the four water ingress and pressure sensors will be monitored for the entire test. Any water leakage into any one of the compartments will be considered a failure. If a leak is detected, the WEC will be immediately deballasted and towed back to dock.

7.1.2 Stability and Seakeeping: c.2 Stability

A great deal of modeling went into the design of the WEC, but before confidence is gained for long-term testing of the physical prototype, it is necessary to validate the stability of the platform. Therefore, for this test, two composite cross beams have been attached to the upper support frame, about 3 m above the water. They are oriented perpendicular to each other. Each of these beams has two water bladders along each beam. Water will be pumped into these bladders and the tilt of the WEC measured.

State of WEC: Nonoperating with paddle locked in the home position.

Instruments: The WEC DAS will be used to record the tilt and draft of the WEC.

Methodology: Fill the bladders until they are completely full according to the capture matrix, and take five minutes of data for each combination of bladders. Repeat if possible.

Table 11. Capture Matrix for the Stability Testing of the WEC

Full Bladders	Tilt of WEC	Draft of WEC
All empty		
1		
2		
1 and 2		
All empty		
3		
4		
3 and 4		

Full Bladders	Tilt of WEC	Draft of WEC
All empty		
1 and 3		
2 and 4		
1, 2 ,3, and 4		
All empty		

7.1.3 Stability and Seakeeping: c.4 Ballasting and Deballasting

The purpose of this test is to monitor the ballasting and de-ballasting and confirm the motions are as predicted by models.

State of WEC: Nonoperating with paddle locked in the home position.

Instruments: The WEC DAS will record the state of the ballasting valves via the Bachmann controller, as well as the WEC position and motion. In parallel, and as part of the loads testing, the loads in all strain gauges and load cells (detailed in the WAV-WALL 2000 NNMREC testing instrumentation document), will be recorded for subsequent analysis and comparison with design cases.

Methodology: The ballasting valves will be actuated as per the procedure in the WAV-WALL 2000 operating manual. Simultaneously, the DAS will record all relevant data for post-test analysis. All ballasting operations will be video recorded from the tow vessel.

7.1.4 Sensors: d.1 DAS, Sensor, and Instrumentation Operation

The purpose of this test is to build upon the wet test and further detect any water-related malfunctions of the DAS when under tow and when ballasted to its full vertical position. It is not intended to repeat the entire testing of 6.1.6. Therefore, only a subset of the sensor and instrumentation operation shall be performed. The tests to be repeated are:

- System Tests: 1, 2, and 3
- Individual Channel Tests: 1 and 2.

7.1.5 Sensors: d.2 Communication

The purpose of this test is to verify the communication with the WiFi and satellite channels when the WEC is ballasted to its full vertical position. The following tests are to be repeated, once for the WiFi and once for the satellite channel: 1, 2, and 5 of the methodology of test 6.1.7.

7.2 Short and Long Duration Testing

For this set of tests, the WEC, Ocean Sentinel, and TRIAXYS wave buoy will be moored at the test site.

7.2.1 Stability and Seakeeping: c.3 Seakeeping and Response

The purpose of this test is to determine the transient response of the WEC in roll, pitch, surge, and sway while coupled to the mooring lines. The WEC will be pulled to specific angular displacements and then released to initiate a transient response. This test will only be performed once during the long-duration testing.

Maximum Sea State: The pull test shall be performed during calm conditions (less that Sea State 2) to limit the effect of sea state on WEC motion.

State of WEC: Nonoperating with paddle locked in the home position. The mechanical yaw lock must also be engaged.

Instruments: The WEC DAS will be used to record the six Degrees of Freedom (DOF) WEC motions, the mooring line tensions and WEC geodetic positions.

Roll and Pitch Response

Setup for Roll and Pitch: The tow line will be attached at the top of the buoy risers to the pull test ring—this allows the tow hook to slide and self-align with the pull direction. To load the mooring line and achieve the desired tilt angle, the tow vessel will align itself in the direction of pull and slowly increase throttle until the desired angle is reached. A snatch release connected to the vessel end of the tow line will be used to release the line at the desired angle. The HMI computer will be aboard the tow vessel to provide real time data on roll and pitch tilt angles.

Methodology: The combination of the different body symmetry in the lateral and longitudinal directions and the mooring system being symmetric at 120° yields a response that is symmetric about the lateral plane. In addition, the WEC will rotate about the mooring. Therefore, it is necessary to perform the pull test for two different WEC orientations and at three angles relative to the surge direction of the platform for each orientation. Each pull defined in the capture matrix will be repeated three times, and measurement duration for each test shall be three minutes (to allow sufficient time for all transients to damp out).

Table 12. Capture Matrix for Roll and Pitch Tilt Test

WEC Heading (° true)	Pull Angle Relative to the WEC Surge Direction (°)	Tilt Angle			
		Angle 1		Angle 2	
		Roll	Pitch	Roll	Pitch
25	0	0	5	0	10
	90	2	0	4	0
	180	0	-5	0	-10
115	0	0	5	0	10
	90	2	0	4	0
	180	0	-5	0	-10

Surge and Sway Response

Setup for Surge and Sway: The paddle and each vertical riser have pull rings attached near the geometric center of the WEC. A diver will attach a tow line to one of these hooks at a time. To load the mooring line and achieve the desired displacement, the tow vessel will align itself in the direction of pull and slowly increase throttle until the desired displacement is reached. A snatch release connected to the vessel end of the tow line will be used to release the line at the desired displacement. The HMI computer will be aboard the tow vessel to provide real time data displacements.

Methodology: As in the roll and pitch response, it is necessary to perform the pull test for two different WEC orientations and at three angles relative to the surge direction of the platform for each orientation. Each pull defined in the capture matrix will be repeated three times, and measurement duration for each test shall be three minutes (to allow sufficient time for all transients to damp out).

Table 13. Capture Matrix for Roll and Pitch Tilt Test

WEC Heading (° true)	Pull Angle Relative to the WEC Surge Direction (°)	Displacement (m)			
		Displacement 1		Displacement 2	
		Surge	Sway	Surge	Surge
25	0	5	0	10	0
	90	0	5	0	10
	180	-5	0	-10	0
115	0	5	0	10	0
	90	0	5	0	10
	180	-5	0	-10	0

7.2.2 Stability and Seakeeping: c.4 Ballasting and Deballasting

See 7.1.3.

7.2.3 Sensors: d.2 Communication

The purpose of this test is to verify the communication with the cellular communication through the Ocean Sentinel, the WiFi, and the satellite channels when the WEC is in its final deployment state—moored and connected to the Ocean Sentinel. The following tests are to be repeated, once for the cellular, the WiFi, and the satellite channels: 1, 2, and 5 of the methodology of test 6.1.7.

7.2.4 Control

The control testing will be performed as part of the mechanical loads tests, 7.2.6. The control for normal operation, normal startup and shutdown, emergency shutdown, etc., will be used in the load cases. For each load case test, the full range of DAS measurements will be recorded and provide sufficient data for control evaluation.

7.2.5 Power: i.1 Power Performance

The goal of the power performance test is to measure the power matrix, which will then be used to compare to the design power matrix and estimate annual energy production. The International Electrotechnical Commission (IEC) technical committee 114 has developed a technical specification that is used to guide the testing.

- Performance Assessment for Wave Energy Conversion Systems in Open-Sea Test Facilities, European Marine Energy Center
- IEC 61400-12-1, Wind Turbines-Part 12-1: Power Performance Measurements of Electricity Producing Wind Turbines, 2005-12.

Measurements: Simultaneous measurements of the wave climate, the power output from the WEC, wind, current, water depth, and mooring line tensions will be made for this test. It is desired to obtain at least three independent measurements, with a goal of 10, for each bin in the capture matrix. Wave measurements are provided every 20 minutes; therefore, each and every data record within a bin must be 20 minutes in duration and be measured simultaneously with the wave data.

Table 14. Capture Matrix for the Power Performance Testing

Significant Wave Height (m)														
	6.0													
	5.5													
	5.0													
	4.5													
	4.0													
	3.5													
	3.0													
	2.5													
	2.0													
	1.5													
	1.0													
	0.5													
		3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
	Energy Period (s)													

7.2.6 Loads, Response, Wear, and Fatigue: j.1 Mechanical Loads

The primary goal of the mechanical loads monitoring is to measure and characterize the mechanical loads at key locations in order to accurately compare actual loads with load estimates for design load cases (DLCs). A secondary goal is to obtain sufficient data to determine load paths and provide data to validate the fatigue analysis. These data will also feed into future design optimizations.

Measurements: Simultaneous measurements of the strains and accelerations within the structure (detailed in the WAV-WALL 2000 NNMREC testing instrumentation document), wave climate, wind, current, water depth, and mooring line tensions will be made for this test. It is desired to obtain at least three independent measurements, with a goal of 10, for each bin in the capture matrix.

Table 15. Capture Matrix for Normal Operation

Significant Wave Height (m)					
	5.5				
	5.0				
	4.0				
	2.0				
		5.0	8.0	12.0	16.0
	Energy Period (s)				

Table 16. Capture Matrix for WEC Locked Down

Significant Wave Height (m)					
	10				
	7.5				
	5.5				
	4.0				
		8.0	12.0	16.0	20.0
	Energy Period (s)				

Table 17. Capture Matrix for Normal Startup

Significant Wave Height (m)					
	5.0				
	4.0				
	2.0				
		5.0	8.0	12.0	16.0
	Energy Period (s)				

Table 18. Capture Matrix for Normal Shutdown

Significant Wave Height (m)					
	5.5				
	5.0				
	4.0				
	2.0				
		5.0	8.0	12.0	16.0
	Energy Period (s)				

Table 19. Capture Matrix for Emergency Shutdown

Significant Wave Height (m)					
	5.5				
	5.0				
	4.0				
	2.0				
		5.0	8.0	12.0	16.0
	Energy Period (s)				

7.2.7 Loads, Response, Wear, and Fatigue: j.2 Mooring Stiffness

The goal of this test is to measure the “as deployed” mooring stiffness of the WEC by displacing the buoy, and measuring the mooring tension and buoy orientation and position.

Note: This test will be conducted at two times: 1) during the short duration test to verify mooring stiffness and 2) shortly before the end of the testing period. These tests will be used to quantify the effect of creep and changes in the synthetic mooring line properties that occur as the lines are loaded and fatigued. If a large storm moves through that loads the mooring line beyond installation loads, a mooring stiffness test may be conducted soon after to quantify any changes in the properties of the synthetic lines.

Maximum Sea State: The mooring stiffness test shall be performed during calm conditions (less that Sea State 2) to limit the effect of sea state or mooring line tensions.

State of WEC: Nonoperating with paddle locked in the home position.

Instruments: The WEC DAS will be used to record the mooring line tensions and WEC geodetic positions. A load cell in the tow line between boat and connection on buoy shall be used to measure tension, and a GPS on the tow vessel will be used to measure vessel position.

Setup: The tow line will be attached at the top of the buoy risers to the pull test ring, which allows the tow hook to slide and self-align with the pull direction. To load the mooring line, the tow vessel will align itself in the direction of pull and slowly increase throttle until the desired tension is reached.

Methodology: Ideally, the mooring stiffness should mirror about each mooring leg and repeat every 120° of heading. However, because imprecise anchor placement and changes in bathymetry, variations are possible. Therefore, for the first test, the mooring stiffness should be measured every 60º to capture each stiff and compliant direction. To verify the changes in mooring stiffness between a stiff and compliant direction, the stiffness should be measured every 15º between 0º and 60º as measured from the direction of the first pull (the first pull direction is parallel with the southeast mooring leg, but in the opposite direction). Ideally, the towing loads will be 1,000 N (225 lbs), 2,500 N (4,500 lbs), 5,000 N (1,100 lbs), 10,000 N (2,250 lbs), and 20,000 N (5,000 lbs). Each load should be sustained for at least two minutes. If time and weather permit, repeat the tests.

For Table 20, in each cell, log the number of tests and the time, duration, compass heading, and rough line tension of each test.

Table 20. Capture Matrix for the Mooring Stiffness Pull Tests.

Angle Relative to Opposite Direction of the Southeast Mooring Leg	Pull				
	1,000 N	2,500 N	5,000 N	10,000 N	20,000 N
0					
15					
30					
45					
60					
120					
180					
240					
300					

7.2.8 Loads, Response, Wear, and Fatigue: j.2 Mooring Loads

The primary goal of the mooring stiffness monitoring is to measure and characterize the tensile loads in the mooring lines at the fairlead in order to accurately compare actual loads with load estimates for DLCs. A secondary goal is to obtain sufficient data to validate the fatigue and creep analysis of the synthetic mooring lines. These data will also feed into future design optimizations.

Measurements: Simultaneous measurements of the mooring line tension, wave climate, wind, current, and water depth will be made for this test. It is desired to obtain at least three independent measurements, with a goal of 10, for each bin in the capture matrices. Note: There are two capture matrices, one for when the WEC is operating and one for when it is locked down.

Table 21. Capture Matrix for the Mooring Loads, WEC Locked Down

Significant Wave Height (m)	10.0							
	8.0							
	6.0							
	4.0							
	2.0							
		4.0	6.0	8.0	10.0	12.0	14.0	16.0
	Energy Period (s)							

Table 22. Capture Matrix for the Mooring Loads, WEC Operational

Significant Wave Height (m)	6.0													
	5.5													
	5.0													
	4.5													
	4.0													
	3.5													
	3.0													
	2.5													
	2.0													
	1.5													
	1.0													
	0.5													
		3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
	Energy Period (s)													

Appendix 1: Test Instrumentation and Hardware

As mentioned in the test plan, the overall data acquisition consists of NREL MOISyT, which is interfaced to the Bachmann controller via a custom interface application program. An overview of MOISyT is provided in the following section, but the details of the hardware and software layout is provided in the document entitled *MOISyT configuration for WAV-WALL 2000 NNMREC Deployment* (Reference 7 listed in Section 2).

MOISyT Overview

The NREL MOISyT is mounted inside the WEC and is based on National Instruments cRIO hardware and LabVIEW software. MOISyT stores data locally, as well as sends them to the Ocean Sentinel buoy via the umbilical cable connecting the two buoys, where they are then transmitted to the NNMREC base facility. A detailed description of the instrumentation, sensors, sensor locations, electrical schematics, and software can be found in the WAV-WALL 2000 NNMREC testing instrumentation document.

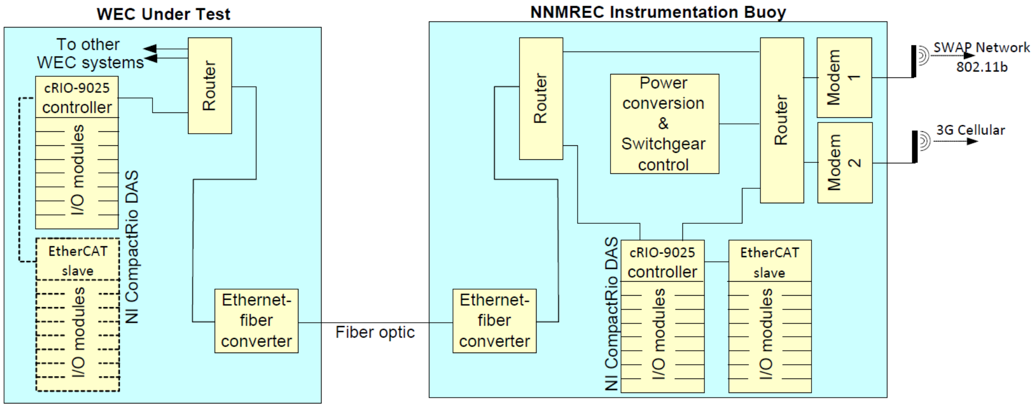


Figure 4. Schematic showing a high-level layout of the WEC and Ocean Sentinel data acquisition systems and interconnections

Source: NNMREC

MOIS consists of a centralized controller and chassis connected to several distributed chassis using Ethernet control automation technology (EtherCAT). EtherCAT is a deterministic industrial communication protocol that extends the Institute of Electrical and Electronics Engineers 802.3 Ethernet standard to transfer data with predicable timing and precise synchronization. Each chassis (including the central chassis) mounts between four and eight industrial input/output (I/O) modules that provide a range of digital and analog I/O. Table 23 lists the locations of each chassis and each module.

Table 23. DAS Component Overview and Configuration

Chassis/Module	Specification
Central Chassis Located in Compartment 2	
Model cRIO-9025 Processor Module	800 MHz processor 4 GB of nonvolatile storage 512 MB of memory One hi-speed USB host port connected to a 2 TB hard drive for extended data storage Dual 10/100BaseTX Ethernet ports One RS-232 port
NI-9870, Four-Port, RS232 Serial Interface Module	Channel 1: DMS Baud rate: 115.2 k Channel 2: Hemisphere VT 101 GPS Baud rate: 9600 Channel 3: Acoustic Altimeter Baud rate: 9600 Channel 4: WEC Controller Baud rate: 115.2 k
NI 9219 24-Bit Universal Analog Input	DAS voltage and current, generator RPM, paddle position, tension in mooring lines, hydrostatic pressure
NI 9208 16-Channel Current Input Module	Generator temperature, torque on input shaft and generator shaft, power, voltage, and current
Remote Chassis Located in Compartment 4	
NI 9219 24-Bit Universal Analog Input	Compartment water ingress
NI 9208 16-Channel Current Input Module	Compartment air temperature and pressure

Pressure Testing Electronics Specification Sheet

FLUKE®

Fluke 719
Electric Pressure Calibrator

Technical Data

One handed pressure calibration

With the innovative, built-in electric pump, the Fluke 719 provides pressure calibration at your fingertips! Now you can calibrate and test pressure devices quickly and easily with one hand, saving you valuable time. Use the programmable pump limit settings to eliminate over-pressurization, and to set 'pump to' pressure values. The unique cleanout port design reduces pump failures, and makes the 719 easy to clean without repair. The compact, lightweight form, combined with one-handed use, makes this pressure calibrator the ideal tool for busy process professionals.

- Electric pump for one handed pressure calibration
- Best in class pressure measurement uncertainty of 0.025 %
- Measure and source mA with best in class 0.015 % accuracy
- Precision pressure adjust vernier
- Variable release rate bleed valve for easy pressure adjustment
- Ideal performance for high accuracy transmitter calibration
- 30 PSI and 100 PSI pressure ranges
- Programmable pump limit:
  - Eliminates over-pressurization
  - Allows the user to program target pressures for pumping
- Extended measurement range with any of twenty-nine (29) 700Pxx Pressure Modules
- Source mA with simultaneous pressure measurement to test valves and I/Ps
- Simulate mA signals to troubleshoot 4-20 mA loops
- Test pressure switches with built in switch test function
- Power transmitters during test using 24 V loop supply
- Proven cleanout ports reduce pump failures

Pump specifications

- Maximum pressure generation of 120 PSI (8 BAR) (100 PSI model)
- Pump to:
  - 30 PSI in less than 15 seconds*
  - 100 psi in less than 45 seconds*

*(with 1 meter of 1/8 inch test hose)

- 5000 pump cycles between rebuilds
- Total pump life 20,000 calibration cycle

General specifications

Storage temperature: -30 °C to 60 °C
Operating temperature: -10 °C to 55 °C
Relative humidity: 95 % (-10 °C to 30 °C); 75 % (30 °C to 40 °C); 45 % (40 °C to 50 °C); 35 % (50 °C to 55 °C)
Shock: 1 meter drop test
Safety: CSA C22.2 No. 1010.1:1992
EMC: EN50082-1:1992 and EN55022:1994 Class B
Size (HxWxL): 60 mm x 87 mm x 210 mm (2.19 in x 3.41 in x 8.28 in)
Weight: 912 g (2 lb)
Battery: Two 9 V alkaline batteries
Battery life: 12 hours with 12 mA into 500 Ω, 200 pump cycles to 100 psi, 500 pump cycles to 30 psi
Warranty: Three-years, one year for pump

Specifications

Function Measure or Source	Range	Resolution	Accuracy	Notes
Fluke-719 30G	-12 to 36 psi, -850 mbar to 2.4 bar	0.001 psi, 0.1 mbar	0.025 % range for 6 months. 0.035 % of range for one (1) year	
Fluke-719 100G	-12 to 120 psi, -850 mbar to 8 bar	0.01 psi, 1 mbar		
mA	0 to 24 mA	0.001 mA	.015 % Rdg + 2 counts	Max load, 1000 Ω 750 Ω ohm in HART mode
Loop supply	24 V dc	N/A	± 10 %	

Ordering information

Fluke-719 30G Electric Pressure Calibrator, 30 psi, 2 bar
Fluke-719 100G Electric Pressure Calibrator, 100 psi, 7 bar

Includes: TL75 Test leads, AC72 Alligator clip set, Push fit connectors, Translucent test hose, Product overview manual (print), and User's manual (CD-ROM) in 14 languages

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Web access: http://www.fluke.com

Specifications subject to change without notice.
Printed in U.S.A. 7/2008 3346371 D-EN Rev A

Appendix 2: Data/Channel List

Table 24. Channel list for the WAV-WALL 2000

Channel Name	Description	Unit	Sensor	Sample Rate	Data File
WEC Control and Power Data					
Time	GPS time stamp	s	PXI GPS	100 Hz	WECvars
GeneratorTemperature	WEC generator temperature	C	NTC 10k	100 Hz	WECvars
GeneratorRPM	RPM of generator	RPM		100 Hz	WECvars
InputTorque	Torque on input shaft	kN m		100 Hz	WECvars
GenTorque	Torque on generator shaft	kN m		100 Hz	WECvars
PaddlePosition1	Angular position of paddle on RHS	deg		100 Hz	WECvars
PaddlePosition2	Angular position of paddle on LHS	deg		100 Hz	WECvars
VoltageCond1	Voltage on conductor 1	V		100 Hz	WECvars
VoltageCond2	Voltage on conductor 2	V		100 Hz	WECvars
VoltageCond3	Voltage on conductor 3	V		100 Hz	WECvars
CurrentCond1	Current on conductor 1	A		100 Hz	WECvars
CurrentCond2	Current on conductor 2	A		100 Hz	WECvars
CurrentCond3	Current on conductor 3	A		100 Hz	WECvars
RealPower	Real power	kW		100 Hz	WECvars
ReacPower	Reactive power	kW		100 Hz	WECvars
WEC Health and System Data					
Time	GPS time stamp	s	PXI GPS	1 Hz	WECstat
WECStatus	Status of the WEC	ASCII #		1 Hz	WECstat
DASStatus	Status of DAS	ASCII #		1 Hz	WECstat
DASVoltage	DAS power voltage	V		1 Hz	WECstat
DASCurrent	DAS power current	A		1 Hz	WECstat

TempCompartment1	Air temperature in compartment 1	C		1 Hz	WECstat
PresCompartment1	Air pressure in compartment 1	kPa		1 Hz	WECstat
WaterCompartment1	Water ingress sensor in compartment 1	binary		1 Hz	WECstat
TempCompartment2	Air temperature in compartment 2	C		1 Hz	WECstat
PresCompartment2	Air pressure in compartment 2	kPa		1 Hz	WECstat
WaterCompartment2	Water ingress sensor in compartment 2	binary		1 Hz	WECstat
TempCompartment3	Air temperature in compartment 3	C		1 Hz	WECstat
PresCompartment3	Air pressure in compartment 3	kPa		1 Hz	WECstat
WaterCompartment3	Water ingress sensor in compartment 3	binary		1 Hz	WECstat
WEC Position and Motion Data					
Time	GPS time stamp	s	PXI GPS	20 Hz	DMS
GPSLatitude	Latitude of WEC	dec deg	Hemisphere VT101	20 Hz	DMS
GPSLongitude	Longitude of WEC	dec deg	Hemisphere VT101	20 Hz	DMS
GPSStatus	Status of GPS	ASCII #	Hemisphere VT101	20 Hz	DMS
WECRoll	Roll of frame	deg	Teledyne DMS-05	20 Hz	DMS
WECPitch	Pitch of frame	deg	Teledyne DMS-05	20 Hz	DMS
WECHeading	Heading of frame	deg	Teledyne DMS-05	20 Hz	DMS
WECSurge	Surge of the WEC frame	cm	Teledyne DMS-05	20 Hz	DMS
WECSway	Sway of the WEC frame	cm	Teledyne DMS-05	20 Hz	DMS
WECHeave	Heave of the WEC frame	cm	Teledyne DMS-05	20 Hz	DMS
Angular Rate X	Frame X angular rate	.01 deg/s	Teledyne DMS-05	20 Hz	DMS
Angular Rate Y	Frame Y angular rate	.01 deg/s	Teledyne DMS-05	20 Hz	DMS

Angular Rate Z	Frame Z angular rate	.01 deg/s	Teledyne DMS-05	20 Hz	DMS
Acceleration X	Frame X acceleration	mm/s^2	Teledyne DMS-05	20 Hz	DMS
Acceleration Y	Frame Y acceleration	mm/s^2	Teledyne DMS-05	20 Hz	DMS
Acceleration Z	Frame Z acceleration	mm/s^2	Teledyne DMS-05	20 Hz	DMS
Status	DMS status	na	Teledyne DMS-05	20 Hz	DMS
IMU Temp	DMS temperature	.01 C	Teledyne DMS-05	20 Hz	DMS
DMS_GPSTime	GPS time from hemisphere VT101	S	Teledyne DMS-05	20 Hz	DMS
HullAltitude	Altitude of bottom of WEC above sea floor	m	Acoustic altimeter	20 Hz	DMS
WaterPressure1	Hydrostatic water pressure 2 m above WEC bottom	bar		20 Hz	DMS
WaterPressure2	Hydrostatic water pressure 2 m above WEC bottom	bar		20 Hz	DMS

WEC Loads

Time	GPS time stamp	s	PXI GPS	100 Hz	WECLoads
TensionLeg1	Tension in mooring leg 1	N		100 Hz	WECLoads
TensionLeg2	Tension in mooring leg 2	N		100 Hz	WECLoads
TensionLeg3	Tension in mooring leg 3	N		100 Hz	WECLoads

Table 25. Channel List for the NNMREC Ocean Sentinel Buoy

Channel Name	Description	Unit	Sensor	Sample Rate	Data File
Ocean Sentinel Environmental Measurements					
Time	GPS time stamp	s	Ocean Sentinel PXI GPS	100 Hz	WSBdata
WSStatus	Status of the Ocean Sentinel	ASCII #		1 Hz	WECstat
WindSpeed1	Anemometer 1 speed	m/s		20 Hz	WSBdata
WindDir1	Anemometer 1 direction	Deg true		20 Hz	WSBdata
WindSpeed2	Anemometer 2 speed	m/s		20 Hz	WSBdata
WindDir2	Anemometer 2 direction	Deg true		20 Hz	WSBdata
VoltageCond1	Voltage on conductor 1	V		100 Hz	WECvars
VoltageCond2	Voltage on conductor 2	V		100 Hz	WECvars
VoltageCond3	Voltage on conductor 3	V		100 Hz	WECvars
CurrentCond1	Current on conductor 1	A		100 Hz	WECvars
CurrentCond2	Current on conductor 2	A		100 Hz	WECvars
CurrentCond3	Current on conductor 3	A		100 Hz	WECvars
RealPower	Real power	kW		100 Hz	WECvars
ReacPower	Reactive Power	kW		100 Hz	WECvars

Table 26. Channel List for the AXYS Wave Buoy

Channel Name	Description	Unit	Sensor	Sample Rate	Data File
AXYS Wave Buoy Measurements					
P_H3	Significant wave height	m	AXYS Wave Buoy	20 min	AXYS_WAVE
P_H10	Mean of highest 1/10	m	AXYS Wave Buoy	20 min	AXYS_WAVE
P_Hmax	Maximum observed	m	AXYS Wave Buoy	20 min	AXYS_WAVE
P_Tm02	Mean wave period	s	AXYS Wave Buoy	20 min	AXYS_WAVE
P_Tp	Peak spectral energy period	s	AXYS Wave Buoy	20 min	AXYS_WAVE
P_Tz	Period of zero crossing	s	AXYS Wave Buoy	20 min	AXYS_WAVE
P_DirTp	Direction at peak spectral energy	deg	AXYS Wave Buoy	20 min	AXYS_WAVE
P_SprTp	Spreading at peak spectral energy	deg	AXYS Wave Buoy	20 min	AXYS_WAVE
P_MainDirection	Main wave direction	deg	AXYS Wave Buoy	20 min	AXYS_WAVE
P_UniDirectivity	Unidirectivity index	na	AXYS Wave Buoy	20 min	AXYS_WAVE
P_UniStartFrequency	Lowest frequency in spectrum	Hz	AXYS Wave Buoy	20 min	AXYS_WAVE
P_UniStepFrequency	Frequency resolution of spectrum	Hz	AXYS Wave Buoy	20 min	AXYS_WAVE
P_UniNumberOfFrequencies	Number of frequency points		AXYS Wave Buoy	20 min	AXYS_WAVE
P_UniFrequencyN_Energy		cm^2/Hz	AXYS Wave Buoy	20 min	AXYS_WAVE
P_ UniSpectrumBiasType			AXYS Wave Buoy	20 min	AXYS_WAVE
P_ UniProcessingMethod			AXYS Wave Buoy	20 min	AXYS_WAVE
P_ UniFrequencyLow		Hz	AXYS Wave Buoy	20 min	AXYS_WAVE
P_ UniFrequencyHigh		Hz	AXYS Wave Buoy	20 min	AXYS_WAVE