
Extreme Conditions Modeling Workshop Report

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Technical Report

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July 2014

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Executive Summary

Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) hosted the Wave Energy Converter (WEC) Extreme Conditions Modeling (ECM) Workshop in Albuquerque, New Mexico on May 13–14, 2014. The objective of the workshop was to review the current state of knowledge on how to numerically and experimentally model WECs in extreme conditions (e.g. large ocean storms) and to suggest how national laboratory resources could be used to improve ECM methods for the benefit of the wave energy industry. More than 30 U.S. and European WEC experts from industry, academia, and national research institutes attended the workshop, which consisted of presentations from WEC developers, invited keynote presentations from subject matter experts, breakout sessions, and a final plenary session.

The key findings and recommendations from the workshop were:

- The wave industry understands that ECM is a critical step in the device design process.
- Numerical and experimental ECM methods developed by the offshore oil & gas and shipping industries, while useful, do not meet the needs of the WEC industry. Accordingly, research is needed to develop WEC-specific ECM methods.
- Open-source experimental data sets are needed to validate WEC device design and analysis methods. The national labs could assist the industry by developing these data sets.
- The WEC industry would benefit from a set of guidelines and best practices that describe how to numerically model WECs in extreme conditions.
- It is difficult to determine what meteorological and oceanographic conditions result in extreme loads on WEC devices. For example, it is not always the largest wave that causes the largest load, making it difficult to determine what wave conditions should be considered when performing survival analysis. The industry would benefit from research that helped develop methods of identifying when extreme events will occur.
- Certification bodies are starting to move towards risk-based certification of WEC devices and WEC developers should adopt a risk-based design approach. Many developers are already beginning to use this approach.
- Uncertainty in how to design WEC devices to survive extreme conditions is slowing the pace of technology development by increasing the investment risk.

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Nomenclature

CFD	Computational fluid dynamics
DLC	Design load condition
DOE	U.S. Department of Energy
DOFs	Degrees-of-freedom
ECM	Extreme conditions modeling
ESS	Extreme sea state
FMEA	Failure mode and effects analysis
IEC	International Electrotechnical Commission
ITTC	International Towing Tank Conference
JIP	Joint industry project
Met-ocean	Meteorological and oceanographic
NREL	National Renewable Energy Laboratory
OWC	Oscillating water column
O&M	Operations & maintenance
PCC	Power conversion chain
PTO	Power take-off
QOI	Quantity of interest
SNL	Sandia National Laboratories
WEC	Wave energy converter

1 Introduction

Wave energy converters (WECs), which convert the kinetic energy in ocean waves into electricity, are designed to maximize fluid-structure interactions between the device and the ocean wave environment in order to optimize energy production. As a result, the hydrodynamic loads WECs experience during both normal operation and extreme conditions must be carefully considered during the device design process. Under most operational conditions, the relevant fluid-structure interactions can be modeled using common numerical and experimental methods [1]–[6]. Conversely, under extreme conditions, WEC devices experience large amplitude motions, wave overtopping, wave slamming, and other physical phenomena that are difficult to accurately simulate. These extreme conditions often determine the maximum design loads, and accordingly, the prediction of extreme loads is a critical step in the device design process.

The WEC industry has adopted extreme conditions design, modeling, and analysis techniques developed for offshore oil & gas and naval architecture applications. While leveraging these existing design and modeling methodologies has greatly benefited the WEC industry in its nascent stages of development, extreme conditions modeling (ECM) methods must be further developed in order to advance technologies towards commercial viability [7].

To assess the ECM needs of the wave energy industry, Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) held an ECM workshop in Albuquerque, New Mexico on May 13–14, 2014. ECM involves several different disciplines, including numerical, experimental, and meteorological and oceanographic (met-ocean) modeling. It also takes into consideration design standards and identification of extreme loading conditions. As described in this report, the workshop was explicitly structured to address each of these topics.

1.1 Objectives

The overall goal of the ECM workshop was to identify research pathways through which national laboratory resources and expertise can be used to improve ECM methods for the benefit of the wave energy industry.

The specific objectives of the workshop were to:

- Review current practices and the state-of-the-art in experimental and numerical modeling methods for predicting device loads, motions, and performance in extreme conditions
- Identify challenges and gaps in the current modeling methods
- Identify research pathways that have the potential to advance ECM methods.

1.2 Definition of Extreme Conditions and Extreme Conditions Modeling

For the purposes of this document, extreme conditions are defined as met-ocean conditions that cause large loads (i.e. loads near or at the design limits) on a WEC device or any of its components. Accordingly, extreme conditions include large ocean storms where large device motions, wave slamming, and wave overtopping occur. Following this definition, extreme conditions may also include operational met-ocean conditions that cause device resonance.

Extreme conditions modeling methods are, therefore, considered to be any numerical or experimental methods that can be used during the design process to predict loads during extreme sea states. Because extreme conditions often result in hydrodynamic loads due to nonlinear phenomena (e.g., wave slamming and overtopping), most extreme modeling methods must be able to accurately model these nonlinear phenomena.

1.3 Report Format

The remainder of this document describes the workshop proceedings, findings, and recommendations. Section 2 provides a description of the workshop. Section 3 then presents the key findings and recommendations from the workshop. The workshop's agenda, list of attendees, session notes, and the responses from the post-workshop questionnaire are presented in Appendices A – D, respectively. In addition, all workshop information, including presentation slides, can be accessed via the workshop website (http://en.openei.org/wiki/Wave_Energy_Converter_Extreme_Conditions_Modeling_Workshop). While some references are cited within this report, a more complete review of useful publications is presented in [8].

2 Workshop Description

The ECM workshop was attended by more than 30 wave energy experts from industry, academia, and national research institutes. A full list of participants and their affiliations is presented in Appendix B.

The workshop was divided into four sessions: (1) presentations from WEC developers, (2) invited keynote presentations, (3) breakout sessions, and (4) a final plenary session. The remainder of this section describes each session in detail. The full workshop agenda is presented in Appendix A. Other workshop documents can be downloaded from the workshop website (http://en.openei.org/wiki/Wave_Energy_Converter_Extreme_Conditions_Modeling_Workshop).

2.1 Developer Presentations

The workshop began with presentations from WEC technology developers Pelamis Wave Power, Resolute Marine Energy, Columbia Power Technologies, and WaveBob (see Table 1). These presentations focused on the specific ECM experience and design methods used by each developer. The developer presentations were followed by a presentation by Ryan Coe from SNL summarizing the NREL and SNL perspective on WEC survival analysis.

Table 1. Developer Presentation Details.

Developer	Speaker
Pelamis Wave Power	Chris Retzler
Resolute Marine Energy	Darragh Clabby
Columbia Power Technologies	Pukha Lenée-Bluhm
WaveBob	Jochem Weber

2.2 Invited Keynote Presentations

Following the developer presentations, invited keynote presentations on numerical modeling, experimental modeling, met-ocean analysis, and offshore oil & gas experience were given by Armin Troesch (University of Michigan), Joop Helder (MARIN), Jim Thomson (University of Washington), and John Halkyard¹ (Halkyard Associates), respectively. These presentations provided the attendees with background on the state-of-the-art WEC ECM methods and set the stage for the breakout sessions.

2.3 Breakout Sessions

After the developer and keynote presentations, the workshop participants formed four breakout groups based on their specific area of expertise.

Numerical modeling: This group focused on all aspects of numerical modeling relevant to ECM. Numerical modeling tools, ranging from high-fidelity models, such as Navier-Stokes computational dynamics, to reduced-order methods, such as potential flow simulations, were discussed.

Physical model testing: This group focused on all aspects of wave tank testing of WEC devices in extreme conditions. Bench-top and dry testing methods were also discussed.

Design standards and extreme loading conditions: This group covered design standards as they apply to the design and analysis of WEC devices in extreme conditions. This group also considered the problem of how to define the conditions that cause extreme loads, addressing the well-recognized issue that the largest loads on a device may not be caused by the largest wave.

Met-ocean modeling: This group discussed current practices and new developments in estimating extreme sea states (ESS) through met-ocean measurements and modeling.

Each breakout group was tasked with answering the following questions with respect to their specific topic:

- What is the current practice and state-of-the-art?
- What are the gaps and obstacles; how should they be prioritized?
- What are the desired outcomes of a concerted research and development (R&D) effort?
- What specific activities are needed to move forward and in what timeframe?

Each attendee selected a breakout session in which to participate. Attendees were encouraged to split their time between multiple breakout sessions if they felt they could contribute in more than one area. Each breakout session was led by an NREL or SNL staff member (see Table 22) who was responsible for taking notes during the session and for presenting the group's findings to the entire workshop in the final plenary session (see Section 2.4). Key findings, recommendations and notes from each breakout session are presented in Appendix C.

¹ Dominique Roddier gave John Halkyard's presentation as Mr. Halkyard was unable to attend the workshop.

Table 2. Breakout Session Group Moderators.

Breakout Session	Group Moderator
Numerical Modeling	Ryan Coe (SNL)
Physical Model Testing	Michael Lawson (NREL)
Design Standards	Jochem Weber (NREL)
Met-ocean	Vince Neary (SNL)

2.4 Final Plenary Session

Following the breakout sessions, the entire workshop reconvened to review the findings of the breakout sessions and for a final group discussion. During the plenary session, each breakout session leader gave a summary of the discussion and conclusions from their respective breakout session. The key findings and recommendations for ECM research, based on the discussion during the final plenary session, are provided in Section 3.

2.5 Post-Workshop Questionnaire

At the conclusion of the workshop, the attendees were strongly encouraged to complete the online survey available at <http://goo.gl/H0oRtv> and shown in Appendix D, which also includes anonymized survey responses from the participants. Significant feedback from the survey is included in Section 3, Key Findings and Recommendations to National Laboratories.

3 Workshop Findings and Recommendations

The workshop presentations, notes from the breakout sessions and plenary session (Appendix C), and the responses to the post-workshop questions (Appendix D), were thoroughly reviewed by SNL and NREL to identify key findings and recommendations that can help the national labs direct resources in a manner that best addresses the ECM needs of the wave energy industry. This section presents these findings and recommendations in detail. Also note that key findings and recommendations from each breakout session are presented in Appendix C.

3.1 Key Findings

1. **The wave industry understands the importance of ECM during the design process:** The industry is aware that ECM must be performed to estimate design loads, but research is needed to identify what conditions result in extreme loads and how to accurately model WECs in extreme conditions using numerical and experimental methods.
2. **Existing ECM methods do not meet industry needs:** The WEC industry is currently using ECM methods adopted from oil & gas, shipping, and naval architecture, but additional research is needed because the physics of wave energy devices are different from most traditional offshore devices (ships and oil & gas platforms). Specifically:
 - a. A dichotomy exists in the design drivers for WECs and traditional offshore devices. WECs are generally designed to maximize fluid-structure interactions in order to maximize power performance, while traditional offshore devices are generally designed to minimize fluid-structure interactions for survivability.

- b. Ships and offshore platforms have a much larger scale than WECs, resulting in different Reynolds numbers and differences in the importance of viscous effects. In addition, the characteristic dimensions of WEC devices are typically smaller than a wavelength, whereas the characteristic dimension of ships and offshore platform are comparable to or larger than a typical wavelength.
 - c. WEC types and environments can vary greatly from moored surface deployments to seabed-mounted deployments, varying water depths, near shore and in shoaling conditions, thus requiring highly flexible modeling tools.
 - d. WECs tend to undergo large amplitude motions, and nonlinear hydrodynamic effects are therefore generally more important for WEC devices than other offshore structures.
- 3. **Open-source experimental data sets are needed:** Although there are several proprietary data sets from extreme conditions testing, there are no open-source (i.e. publically available) data sets.
- 4. **There are no guidelines for numerical modeling of WECs in extreme conditions:** Although there are a number of modeling methods capable of simulating the performance of WECs in extreme conditions (e.g. computational fluid dynamic [CFD] codes), there are no clear guidelines for how to perform ECM analyses. Most WEC companies are small, with limited in-house numerical modeling expertise and resources, and as such, the industry would benefit from guidelines on how to use existing numerical tools to model extreme events.
- 5. **Extreme sea state characterization for WEC modeling is a challenge:** Buoy observations are point measurements (they are therefore limited in spatial coverage) and may not represent extreme sea states at WEC deployment locations. Moreover, in order to get statistically significant data with which to estimate 25-, 50-, or 100-year storm conditions, long measurement histories (e.g. 20 years) are needed. Unfortunately these measurement histories do not typically exist at wave energy testing, demonstration, and potential commercial sites.
- 6. **Predicting the conditions that cause extreme loads is difficult:** It is not always the largest wave that causes extreme loads and more often it is a specific wave train. For example, one wave may position a WEC into a vulnerable position and a following wave, that would not normally damage the device, may impact the device in a way that causes an extreme loading event. In other words, the largest wave is not always the most harmful, and the operational design space must be searched to identify the sea states and wave trains that will most likely cause a failure of the WEC system. This contrasts with the extreme conditions analysis for the offshore oil & gas industry, which are generally defined by the largest expected wave (often the 1,000- or 10,000-year wave).
- 7. **The uncertainty of how to design for extreme conditions is slowing the pace of technology development by increasing the investment risk:** A device failure during a field deployment can cause serious harm to the reputation of wave energy companies and decrease the chance of private and public investment, even if the experience gained from device or system failures during testing is valuable. Accordingly, developing improved ECM

methods that decrease the uncertainty associated with ECM will significantly benefit the wave energy industry.

3.2 Recommendations to the National Laboratories

1. **Create a U.S. “MARINET-like” program:** The U.S. industry would benefit greatly from a testing program similar to the EU MARINET program (<http://www.fp7-MARINET.eu/>). This type of program would provide free access to wave tanks and expertise on how to perform experiments and numerical modeling in operational and extreme conditions. The vast majority of workshop attendees felt this type of program would be very valuable. The need for such a program may, to some extent, be met by the DOE WEC-Prize competition.
2. **Generate open-source WEC data sets:** There are few, if any, high-quality publically available data sets that can be used for numerical model validation. The industry would benefit greatly from open-source data for WECs in both extreme and operational conditions. The proposed US “MARINET-like” program from recommendation 1 could supply these datasets if the data is required to be made publically available.
3. **Initiate a WEC code-comparison project:** The WEC modeling community would benefit from a WEC code-comparison project that is similar to the Offshore Code Comparison Collaborative projects (OC3, OC4, and OC5) that have verified a wide spectrum of wind turbine models/assumptions against baseline tank tests. As demonstrated by OC3, OC4, and OC5, code comparison projects are very useful not only for validating codes, but also for identifying areas where existing modeling methods need to be improved.
4. **Develop efficient methods to search the design space for expected met-ocean conditions that are likely to cause extreme loading:** Methods are needed to efficiently search the operational and survival design spaces for scenarios that pose a threat to WEC survival. One example of this type of method is the Design Loads Generator developed at the University of Michigan [10].
5. **Build on existing offshore marine structures experience, guidelines, and standards for extreme sea state characterization:** For ESS characterization, current practices for offshore marine structures [11]–[15] can be directly adapted. These include: (1) Use of hindcast simulations or buoy observations of sufficient duration (20 years preferred) and appropriate locations; (2) Extreme value theory and models used for extrapolation to events more extreme than those observed in a shorter period of record; (3) Contours in the environmental space (usually significant wave height and peak period) from which sea states that elicit extreme response can be derived; (4) Identification of one or more ESS (e.g., Hs100, T100) to describe single extreme wave or wave group (with assumed wave spectrum) as input for numerical or physical model simulation.
6. **Numerical and experimental modeling guidelines and design standards are needed:** Several numerical and experimental modeling methods are capable of predicting loads during extreme events. In addition, there are several design guidelines for WEC devices [10]–[14]. However, there are no well-documented procedures for how to use the existing modeling methods or standards to design WEC devices. The wave energy industry would benefit greatly from the development of an ECM recommended practices document as well as example analyses. In addition, existing offshore standards should be reviewed to

determine what standards can be used by the WEC industry and in what areas new standards are needed. This need is being partially met by IEC-TC114.

7. **Encourage the WEC industry to adopt risk-based design methodologies from shipping and offshore oil & gas industries:** The WEC industry and certification agencies are beginning to adopt risk-based design and device certification strategies pioneered by other offshore industries. The challenge of implementing a risk-based approach within the WEC industry lies in both the execution of the process and ensuring new frontiers related to WEC devices are considered and well understood. With a risk-based method, the likelihood and consequence of device and/or system component failures is evaluated with respect to the social, environmental, and economic impact of the failure. The risk-based design approach should employ estimates from the best available ECM methods and predictions of operational loads.

4 Conclusion

The ECM Workshop provided a forum for experts from industry, academia and research institutions to discuss the current state of ECM knowledge and to suggest future research paths to benefit the wave energy industry. Several shortcomings in existing WEC ECM methods were identified during the workshop and the workshop attendees identified and recommended research paths to help address the shortcomings. The recommendations developed during the ECM workshop span the sub-disciplines that comprise ECM (numerical and physical modeling, extreme sea state characterization and design standards). Successful execution of these recommendations will help advance wave energy technologies towards commercial viability.

Acknowledgements

The National Renewable Energy Laboratory and Sandia National Laboratories would like to thank all the workshop attendees, who generously took two days out of their busy schedules to share their knowledge and expertise in the area of WEC extreme events modeling.

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Appendix A Workshop Agenda

Day 1 - Tuesday, May 13th					
Time	Topic (location)				Speaker/s
7:15 – 8:15 AM	Breakfast (Majorca Foyer)				
8:30 - 8:45 AM	Welcome and Opening Remarks (Majorca)				Daniel Laird, SNL
					Ben Maurer, DOE
8:45 - 9 AM	WEC Developer Experience: Pelamis Wave Power (Majorca)				Chris Retzler
9 - 9:15 AM	WEC Developer Experience: Columbia Power Technologies (Majorca)				Pukha Lenée-Bluhm
9:15 - 9:30 AM	WEC Developer Experience: Resolute Marine (Majorca)				Darragh Clabby
9:30 - 9:45 AM	WEC Developer Experience: NREL/WaveBob (Majorca)				Jochem Weber
9:45 - 10:15 AM	National Lab Perspective & Discussion (Majorca)				Ryan Coe
10:15 - 10:30 AM	Coffee break (Majorca Foyer)				
10:30 - 11 AM	Keynote on Offshore Oil & gas Experience (Majorca)				John Halkyard, Halkyard Assoc.
11 - 11:30 AM	Keynote on Tank Testing (Majorca)				Joop Helder, MARIN
11:30 AM - 12 PM	Keynote on Numerical Modeling (Majorca)				Armin Troesch, U. of Michigan
12 - 1 PM	Lunch (Casablanca)				
1 - 1:30 PM	Keynote on Met-Ocean (Majorca)				Jim Thomson, U. of Washington
1:30 - 1:45 PM	Break-Out Group Logistics and Objectives (Majorca)				
1:45 - 3 PM	Breakout Groups				
	Physical Model Testing	Numerical Simulation	The Role of Design Standards & Identification of Extreme Loading Conditions	Extreme Sea State Characterization	
3 - 3:15 PM	Coffee break (Majorca Foyer)				
3:15 - 5 PM	Breakout Groups				
	Physical Model Testing	Numerical Simulation	The Role of Design Standards & Identification of Extreme Loading Conditions	Extreme Sea State Characterization	
5 - 5:15 PM	Day 1 Debrief and Group Discussion (Majorca)				NREL & SNL
7 – 9 PM	Group Dinner				

Day 2 - Wednesday, May 14th					
Time	Topic				Speaker
7:15 – 8:15 AM	Breakfast (Majorca Foyer)				
8:45 - 9 AM	Review Day 2 Agenda and Objectives, Review Day 1 Findings and Readjust Groups as Needed (Majorca)				NREL & SNL
9 - 10:30 AM	Breakout Groups				
	Physical Model Testing	Numerical Simulation	The Role of Design Standards & Identification of Extreme Loading Conditions	Extreme Sea State Characterization	
10:30 - 10:45 AM	Coffee break (Majorca Foyer)				
10:45 AM - 12 PM	Breakout Groups				
	Physical Model Testing	Numerical Simulation	The Role of Design Standards & Identification of Extreme Loading Conditions	Extreme Sea State Characterization	
12 - 1 PM	Lunch (Casablanca)				
1 - 1:30 PM	Physical Model Testing Group Presentation and Discussion (Majorca)				Michael Lawson
1:30 - 2 PM	Numerical Simulation Group Presentation and Discussion (Majorca)				Ryan Coe
2 - 2:30 PM	Design Standards Group Presentation and Discussion (Majorca)				Yi-Hsiang Yu
2:30 - 3 PM	Identification of Extreme Loading Conditions Group Presentation and Discussion (Majorca)				Jochem Weber
3 - 3:30 PM	Extreme Sea State Characterization Presentation and Discussion (Majorca)				Vince Neary
3:30 - 5 PM	Final Discussion and Next Steps (Majorca)				NREL & SNL

Appendix B Workshop Attendees

Name	Organization
Paul Liu	NOAA Great Lakes Environmental Research Laboratory
Lance Manuel	University of Texas at Austin
Eric Paterson	Virginia Tech
Arnie Fontaine	Penn State - Applied Research Lab
Rob Kuntz	Penn State - Applied Research Lab
Pukha Lenée-Bluhm	Columbia Power Technologies
Darragh Clabby	Resolute Marine
Chris Retzler	Pelamis
John Halkyard	Halkyard Associates
Dominique Roddier	Principle Power
Marco Masciola	American Bureau of Shipping
Jarett Goldsmith	DNV GL
Gaizka Zarraonandia	DNV GL
Thomas Fu	Office of Naval Research
Armin Troesch	University of Michigan
Jim Thomson	University of Washington
Aurélien Barbarit	Ecole Central de Nantes
Joop Helder	MARIN
David Newborn	Naval Surface Warfare Center - Carderock
Miguel Quintero	Naval Surface Warfare Center - Carderock
Ken Weems	Leidos
Ronan Costello	National University of Ireland, Maynooth
Solomon Yim	Oregon State University
Mirko Previsic	Re Vision
Bryson Robertson	University of Victoria
Vince Neary	Sandia National Laboratories
Ryan Coe	Sandia National Laboratories
Daniel Laird	Sandia National Laboratories
Diana Bull	Sandia National Laboratories
Yi-Hsiang Yu	National Renewable Energy Laboratory
Michael Lawson	National Renewable Energy Laboratory
Jochem Weber	National Renewable Energy Laboratory

Appendix C Detailed Breakout Session Findings and Notes

This appendix presents the notes and presentation materials from the breakout sessions. The notes were lightly edited after the workshop for clarity and grammar, but care was taken not to modify the technical content. While some references are cited within this report, a more complete review of useful publications is presented in [8].

C.1 Numerical Modeling

C.1.1 Participants

The numerical modeling breakout group was composed of the following participants:

Participant	Organization
Aurélien Barbarit	Ecole Central de Nantes
Ryan Coe (moderator)	Sandia National Labs
Rob Kuntz	Penn State ARL
Daniel Laird	Sandia National Labs
Pukha Lenée-Bluhm	Columbia Power Technologies
David Newborn	Naval Surface Warfare Center, Carderock
Eric Paterson	Virginia Tech
Mirko Previsic	Re Vision
Kelley Ruehl (note-taker)	Sandia National Labs
Armin Troesch	University of Michigan
Solomon Yim	Oregon State University
Ken Weems	Leidos

C.1.2 Key Findings and Recommendations

C.1.2.1 Key Findings

- **Lack of experimental data for validation:** Relatively little data is publically available from tests of WECs in extreme conditions with which numerical models can be validated. Publically available datasets from well-documented experimental test campaigns would allow for better validation and thus greatly improve confidence in numerical models.
- **Quantitative relative performance of numerical models:** While there are a range of numerical models available for analysis of a WEC in extreme conditions (see Section **Error! eference source not found.** of the Appendix of this report), their relative performance is not well characterized. To understand how these models should best be used in various scenarios, a more quantitative understanding of their relative performance (including efficiency and accuracy) is needed.
- **Efficient search of survival space:** Testing a survival condition with a model (numerical or experimental) is challenging partially because the most dangerous condition for a specific device cannot be known in advance. Thus part of the problem becomes searching a very large space of possible scenarios for those that pose a threat. The scenarios must be searched are comprised of irregular sea states, winds and currents, each with a distinct angle of incidence. The number of scenarios that must be evaluated prohibits the exclusive use of high-fidelity

numerical and physical models. These more expensive and time-consuming models must be accompanied by more efficient lower-fidelity models, which can help reduce the search space to a more manageable size.

C.1.2.2 Recommendations

- A. Numerical model comparison:** A formal “code comparison” project could be used to provide a quantitative comparison of the various numerical models available for analysis of WECs in extreme conditions. This comparison would focus on a set of representative WEC designs (e.g., DOE Reference Models). Researchers from various institutions would then be asked to use their respective numerical codes to perform a predefined set of analyses. The results of these analyses would then be compared using a common set of metrics. If possible, physical experiments should also be conducted to provide a validation point.
- B. Development/demonstration of efficient survival space search method(s)** – This effort would focus on development and/or demonstration of methods to more efficiently analyze the survival of a WEC for a given deployment location. Two paths were suggested by workshop participants:
 - Lower-fidelity models can be employed to develop response surfaces on which point evaluations can employ higher-fidelity models.
 - High-fidelity models can be employed to find scenarios that may cause failures of the device; searches can then be expanded in that vicinity with lower-fidelity models, using extreme sea state characterization methods to determine event frequency.
- C. Numerical model improvement** – Potential improvements to numerical models include:
 - Viscous damping parameters can be predicted via CFD for use in lower-fidelity models.
 - Wave propagation in CFD simulations can be improved, through domain decomposition or improved boundary condition formulations.

C.1.3 Notes

C.1.3.1 Quantities of Interest

The choice of a numerical model and decisions made in its implementation must take into account the nature of the specific WEC being considered. These decisions can be informed by identifying quantities of interest (QOIs). A general set QOIs for WEC survival include

- **Dynamic response** – The dynamic motion of the various bodies of the WEC as determined from rigid-body inertial properties and global loads. The position of the WEC relative to the free surface is needed to determine the effect of various physical phenomena (e.g., slamming and breaching). This is particularly important for oscillating water columns (due to the importance of sloshing and flooding in the moon pool).
- **PCC & joint loading** – Forces and moments applied at joints and within the power conversion chain are needed for structural analyses.
- **Mooring connection points** – Forces induced mooring connection points on device and sea floor are needed for analysis of a device’s mooring system.

- **Spatial pressure distribution** – Local loads on the hull of the device are needed to inform structural analyses. When necessary, these may include peak impact pressure due to slamming.

C.1.3.2 Key Physical Phenomena

Accurate prediction of these QOIs is dependent on an adequate representation of the physical phenomena that dominate those QOIs. A list of physical phenomena key to the dynamics of WEC in survival conditions are

- **Environment** – The environment at a WEC deployment can be seen as the input to a numerical model.
 - **Waves** – Waves are thought to represent the dominant forcing factor for most WEC survival scenarios. A numerical model must be capable of producing regular and irregular waves with arbitrary directionality.
 - **Wind** – Wind loading on WECs is generally considered to be a marginal component for WEC survival. However, for WECs with large solid areas above the free surface (e.g., OWCs) wind may play a larger role.
 - **Current** – Current, which may occur in a direction different than the primary wave spectrum, must be considered.
- **Hydrodynamics** – Hydrodynamic phenomena are considered to be the dominant component influencing the above listed QOIs.
 - **Wave modeling** – Beyond specifying accurate wave conditions as the input to a model, some models (e.g., free surface Navier-Stokes) require additional consideration as to accurate propagation of waves.
 - **Ideal flow** – Phenomena captured by ideal flow theory must be included.
 - **Hydrostatics**
 - **Froude-Krylov**
 - **2nd-order drift force**
 - **Radiation**

These phenomena can be characterized using frequency-domain boundary element method (BEM) codes (e.g., WAMIT). However, parameters obtained via BEM codes are only truly applicable for small amplitude motions. Models that rely on frequency-domain codes for hydrodynamic parameters can employ additional approximations, in which hydrodynamic parameters are approximated as a function of submerged geometry.
 - **Viscous effects**
 - **Slamming** – Slamming during water reentry and due to steep or breaking waves should be considered, especially when spatial pressure distributions on a WEC's hull are of interest.
 - **Greenwater** – Overtopping can influence local pressures and the dynamic response of a WEC
- **Mooring** – A WEC's mooring system can have a large influence on the dynamic response. Likewise, a mooring system must be designed to withstand loads created by the motions of

the WEC. Additionally, localized loads are mooring connection points that may be of interest.

- **Power conversion chain (PCC)** – Numerical models used in survival analysis must be capable of including arbitrary forcing from a PCC. Many WECs are currently designed to employ survival strategies in the PCC is either “locked” or allowed to “freewheel” to reduce loading. However, research is currently underway to investigate the effectiveness of the life-extending controls (LECs) on WECs, in which the PCC force can be modulated to reduce system loading.
- **Rigid-body motion** – Global loads must be coupled with rigid-body properties to predict the dynamic motion of a WEC. Models should be capable of simulating constrained motion, in which only a subset of the full six degrees-of-freedom (DOFs). Numerical models should also allow for relative motion of two coupled rigid bodies.
- **Structural response** – In some cases, it may be necessary to consider the structural response of a WEC. It is believed that, in most cases, structural analyses can be carried out without direct coupling with hydrodynamic models. Exceptions include highly flexible structures (e.g., Anaconda device) and slamming analyses.

C.1.3.3 Available Numerical Models

A range of numerical models are available for use in the WEC survival analysis process. In general, the cost to run a model (which must include licensing as well as computational and personnel resources) increases with model fidelity. Even with free access to today’s best computational resources and highly-skilled engineers, using the highest-fidelity models for all of the simulations in a WEC survival analysis is impractical, as the models would require many years to run.

- **Frequency-domain (same as time-domain Cummins’)** – These models assume a linear system in which reactions due to radiation and diffraction can be linearly decoupled and superimposed. These assumptions are only valid for bodies in regular waves undergoing small amplitude motion.
- **Semi-empirical time-domain (Cummins’ Eq. w/ nonlinear effects)** – These models have their basis in the same theory used for frequency domain models, but employ Fourier transforms to operate in the time-domain. While time-domain models are based on the assumption of small amplitude motion, augmentations to account for large amplitude motions and nonlinearities are possible.
 - **Nonlinearities** – Nonlinearities that can be added to these models include
 - **Hydrodynamic & hydrostatic** – These phenomena can be made a function of body position.
 - **PCC (control)** – Arbitrary control of the PCC with force and motion saturation.
 - **Mooring** – Mooring models can vary from simple catenary models to fully dynamic models.
 - **Free surface representation** – Nonlinear wave formulations provide a better model of real ocean waves.
- **Nonlinear potential flow** – These models solve an initial boundary value problem by employing a potential flow panel method. Viscous effects must be included empirically.

- **Free surface Navier-Stokes** – These are generally referred to as computational fluid dynamics (CFD) models. Free surface Navier-Stokes models represent the highest fidelity of numerical model applicable to analysis of WECs in extreme conditions. Given the proper configuration, these are capable of capturing the full range of phenomena that affect a WEC in extreme conditions.

C.2 Met-ocean/Extreme Sea State Characterization

C.2.1 Participants

The participants in the Met-Ocean breakout group are listed below:

Participant	Organization
Annie Dallman (note-taker)	Sandia National Labs
Tom Fu	Office of Naval Research
Lance Manuel	University of Texas at Austin
Chris Retzler	Pelamis
Bryson Robertson	University of Victoria
Vincent Neary (moderator)	Sandia National Labs
Jim Thomson	University of Washington

C.2.2 Key Findings and Recommendations

C.2.2.1 Key Findings

- **Current practices for characterizing extreme sea states exist:** Current practices for offshore marine structures, [11]–[15], can be directly adapted for extreme sea state characterization.
- **Return periods for WECs are different than for other structures:** Although 100-yr return period events are common for marine structures, lower return periods can be used, if acceptable for survivability, when the design service life is less than 100 years [DNV 2005]. The acceptable level of risk for WECs can be quantified through a rigorous risk-based assessment that depends on the design service life, cost of device, and consequence class.
- **Improved wave measurement capabilities are needed:** Additional measurements and measurement capabilities are needed to more accurately predict the true distribution of extreme sea states. Buoy observations are point measurements and are therefore limited in spatial coverage, and may not represent ESS at the WEC deployment location. They typically have shorter periods of record than desired for accurate estimates of ESS (less than 20 years). Altimeters and synthetic aperture radar (SAR) measurements offer better spatial coverage, but at a low spatial and temporal resolution, which low pass filters large waves and underestimates ESS. Validated long-duration simulations may be the most practical approach to ESS characterization, but they are also known to under-bias prediction of large waves and underestimate ESS.
- **Ongoing research will improve ESS characterization methods:** Expected advances within the next 5 to 10 years should improve the accuracy of ESS characterization. These advances include the development of improved and more affordable monitoring instruments, improved measurement techniques (e.g., buoy arrays), adoption of higher order spectral methods (e.g.

Janssen and Herbers), improved prediction of breaking waves, improved hindcast models and models that can simulate the effects of WEC device interaction in arrays.

C.2.2.2 Recommendations

- **The WEC industry should leverage existing standards:** Current practices for offshore marine structures [11]–[15] can be directly adapted by the WEC industry, but a consolidation of the existing standards in one location would make the standards easier to understand and use.
- **Research is needed to do the following:**
 - Improve wave measurements and include better quantification of uncertainty of buoy measurements
 - Determine appropriate spectra for modeling extreme wave environments
 - Improve time-domain analysis of buoy data to identify individual waves and wave groups

C.2.3 Notes

The group defined four objectives that aligned with the overarching workshop objectives:

- Define the current state of the art for *extreme sea state characterization* (“current practice”)
- Identify & prioritize *challenges and gaps* (*limitations of current practices*)
- Recommend research pathways to most effectively advance ECM methods, including immediate recommendations for improvement, R&D needs and specific R&D activities (with time frame)

C.2.3.1 Current practices

- Use of hindcast simulations or extreme value analysis to extrapolate buoy measurements
- Extreme value theory and models used for extrapolation to events more extreme than those observed in a shorter period of record
- Use of Inverse FORM technique to define ESS; contours in the environmental space (usually significant wave height and peak period) along which contours of an extreme response with a given return period should lie [12] . Generalized Extreme Value (GEV) distribution, to estimate one variable at a time (not recommended)
- Identify one or more ESS (e.g., Hs100, T100) to describe single extreme wave or wave group (with assumed wave spectrum) as input for numerical or physical model simulation

Due to time constraints, the discussion did not include recommended practices and guidelines for ESS characterization, including guidelines and applicable design standards for offshore structures cited in Reference [11]. These are listed below:

- Guidelines for characterizing ESS are given in Ref. [11], and there are recommended practices and standards for offshore structures listed in Ref. [15] that can be directly adopted.
- Reference [11] defines three WEC deployment environments, bed-deployed-shoreline (surf zone), bed-deployed-shore (shallow water), and moored floating-offshore (deep water).
 - Based on design criteria API RP 2A WSD – Fixed Offshore Structures, the recurrence interval of the ESS should be several times the planned service life of the WEC [15]

- Based on design criteria API RP 2SK – Station keeping Systems for Floating Structures, the recurrence interval design condition for permanent moorings should be determined by a risk analysis taking into account the consequence of failure [15]
- Based on design criteria API RP 2SK – Station keeping Systems for Floating Structures, environmental loads must consider a combination of wave, current and wind conditions causing the extreme load in the design environment [15]
- Based on DNV design guidelines for wave energy converter design (Section 13.9) [11], design of the device should be based on the most severe environmental loads the structure may experience
- Based on design criteria API RP 2SK – Station keeping Systems for Floating Structures, the most severe directional combination of wind, wave and current forces should be specified for the permanent installation [15]
- Based on DNV design guidelines for wave energy converter design (Section 13.9) [11], The proper combinations and joint occurrences of waves and current conditions, as given in DNV-OS-C101 (Design of Offshore Steel Structures, General), should be applied [15]
- Based on DNV design guidelines for wave energy converter design (Section 15.2) [11], for WECs with a dynamic response to wave loading and or novel mooring configuration, a complete time domain simulation combined with tank testing may be necessary
- Based on EMEC guidelines on Reliability, Maintainability and Survivability of Marine Energy Conversion Systems (5.2.2.1), near-shore corrections should be considered before met-ocean data used to represent a site. Wave loading through the water column during storms is of particular importance [15]
- Based on DNV design guidelines for wave energy converter design (Section 15.2) [11], for WECs with a dynamic response to wave loading and or novel mooring configuration, a complete time domain simulation combined with tank testing maybe be necessary
- Based on EMEC – Wave Energy Tank Testing guidelines, (3.1), planned testing should include extreme wave loading of structure [15].

C.2.3.2 Limitations

- ESS characterization in shallow shoaling surf regions with breaking waves is especially challenging
- Buoy data are point measurements
- Extrapolated return periods of ESS are sensitive to the extreme theory or model used
- Wave buoys use different measurement technologies and have different accuracies and resolution
- Sea state measurements are typically over short periods of record less than 20 years
- Archived buoy data only have first five spectral moments (cannot reconstruct 2D phase-resolved wave group, e.g., crossing-seas)
- Long duration hindcast simulations under-bias extreme waves (See comparison of buoy and hindcast H_s plot, Fig. 2.3, M. Prevosto, Extreme and long term extrapolation, EquiMar Deliverable D2.6, January 2011)

- Estimating the loads on offshore structures in extreme irregular waves is sensitive to the wave kinematics model used (C.T. Stansberg, O.T. Gudmestad, S.K. Haver 2008. Kinematics under extreme waves. Trans. of ASME, J. of Offshore Mech. And Arctic Engrg. 130,)
- Archived hindcast simulations are not sufficiently archived (e.g. NOAA only archiving bulk parameters in WW3). Cannot reconstruct spectral shape and random wave field
- Not accounting for ‘rogue waves’ $H > 2.2H_s$ (Rayleigh Distribution), large wave events, breaking, Cahill PhD Dissertation.
- Rarely coupling wave, wind and current loads
- No accounting for spatial variation (arrays) of rogue waves
- No shoaling wave environments.

C.2.3.3 Session overview

WEC survival can be compromised in low and high sea states. This project narrowed the scope to focus on modeling the WEC response to an extreme sea state (ESS) because this entails special considerations and challenges in analysis, including numerical and physical modeling; not only challenges analyzing WEC response, but challenges modeling the extreme sea state as the model input.

The inverse-FORM method is applied to define an extreme sea state condition for a desired WEC deployment location. Device response in these conditions is then assessed with numerical and/or physical models. Numerical models generally consist of low to mid-fidelity codes (see “Semi-empirical time-domain” models in Section C-4.3 of the Appendix of this report). Numerical modeling efforts are generally backed up with model-scale physical testing.

Extreme sea state characterization challenges: Buoy observations are point measurements, are limited in spatial coverage, and may not be representative of ESS at the WEC deployment location. They typically have shorter periods of record (less than twenty years) than desired for accurate estimates of ESS. Altimeters and synthetic aperture radar (SAR) measurements offer better spatial coverage, but at a low spatial and temporal resolution, which low pass filters large waves and underestimates ESS. Validated long-duration hindcast simulations may be the most practical approach to ESS characterization, but they are also known to under-bias prediction of large waves and underestimate ESS.

For ESS characterization, current practices for offshore marine structures [11]–[15] can be directly adapted. Nevertheless, the ESS breakout group outlined the limitations of current practice methods, recommendations for improving ESS characterization, expectations for advancing ESS measurement and modeling techniques and recommended research pathways.

During the breakout group discussion, the following key findings and recommendations were discussed:

- Quantify uncertainty with buoy measurements (e.g., JCOMM)
- Use full (well resolved) spectral information
 - reconstruct complete wave field (nonlinear preferred, but linear ok); At least 100 crests

- Or partition to different unique wave trains (separate swells and wind waves); Way to improve inverse FORM method
- If buoy data can be obtained, use time-domain analysis of buoy data to identify individual waves and groups
 - Use wave time series and zero crossing analysis to identify large waves (e.g., Tucker and Pitt – Cahill Thesis)
- Include wave steepness as additional parameter

C.2.3.4 Expected R&D Advances (time frame)

- 2D phase resolved descriptions (sequence and timing of waves in wave groups), measurement and modeling, 10-year time frame
- Need to reduce cost of instruments, 5-years
- New measurement techniques (Thomson): Doppler radar, scanning LiDAR, buoy arrays, 5-years
- Deployment & adoption of newer measurement devices, 5-years
- Adoption of higher order spectral methods (e.g., Janssen and Herbers), 5-years
- Predictive tools for breaking (measurement and modeling), 5-years
- Improved hindcast models (better wind inputs) to better resolve extreme waves, 5-years
- Array effects on ESS and environmental loading, 5-years
- Improvements in characterizing ESS in near-shore environments, 5-years

C.2.3.5 Research Paths

- Complete review of current practice in seakeeping, offshore oil & gas, offshore wind
- Demonstration project (DOE Reference Model WEC)
 - Improved wave measurement techniques
 - Rough/approximate description of 2D phase resolved wave field
 - Use partitioned spectra to perform Inverse FORM method for site/device pair (DOE reference model, Humboldt Bay)
 - Coupling of wave, current and wind loads
 - Evaluate value of recommendations
 - 5-10 year effort
- Working Group, international Technical Specification on WEC survivability analysis (e.g., IEC, IEA, ISSC, ITTC)
- Identify other international researchers working on extreme sea state analysis

C.3 Physical Modeling

C.3.1 Participants

The participants in the Physical Modeling breakout group are listed below:

Participant	Organization
Michael Lawson (moderator)	National Renewable Energy Laboratory
Diana Bull (co-moderator)	Sandia National Laboratories
Chris Rensler	Pelamis Wave Power
Dominique Roddier	Principle Power
Joop Helder	MARIN
Miguel Quintero	Naval Surface Warfare Center - Carderock
Ronan Costello	National University of Ireland, Maynooth

C.3.2 Key Findings and Recommendations

C.3.2.1 Key Findings

- **Experimental methods being used are from offshore oil & gas and shipping industries:** Developers are using experimental methods developed by the shipping and offshore oil & gas industries.
- **Extreme loads are not necessarily the result of the largest wave:** Extreme loading events are typically a series of waves from a specific wave train as opposed to simply the largest wave. Accordingly, focused waves in a wave tank test may not be the most appropriate way to test device performance in extreme conditions.
- **WECs will not be designed to the same level as ships or offshore platforms:** The industry needs a way to determine what condition to design to (see the risk-based design in the Standards breakout session). In other words, depending on cost and consequence class, should extreme conditions be defined as a 20-year storm, 50-year storm, or 100-year storm. In addition, it is important to develop appropriate safety factors to apply during the extreme loads design process and these factors may be different than those used by the offshore oil & gas and shipping industries.
- **Testing devices with deformable bodies is difficult:** It is difficult to test WECs that rely on deformable body dynamics because of material scaling properties. It is unclear whether there are enough developers perusing this type of technology to justify investment in developing experimental modeling techniques.

C.3.2.2 Recommendations

- **Develop improved methods of modeling power take off systems at small scale:** Power-take-off systems are difficult to test accurately at small scale and R&D and testing methods improvement are needed and should be developed
- **Consolidate existing standards and design guidelines:** There are several design and testing guidelines currently under development (e.g. International Electrotechnical Commission, International Towing Tank Conference, ABS, DNV-GL). However it is not always clear what

standards should be followed and the existing standards should be consolidated in one location (perhaps OpenEI) for clarity.

- **Insure that all measurements are of appropriate time resolution and are time synced:** During testing, all experimental measurements should be time synced.
- **Calibrate wave tanks before testing:** Calibration of wave tanks is critical and it should be confirmed the tank is accurately calibrated before testing begins.
- **Perform numerical simulations at the same time as experimental tests:** Numerical simulations should always be performed simultaneously with wave tank tests so that any problems with the experiments can be identified before testing is complete.
- **Insure PTO systems are accurately modeled in scale experimental tests:** PTO system scaling is very difficult. Scale PTO systems should be constructed very carefully to insure proper performance, or electric motors should be used in place of scale PTO systems to insure the forces acting on the device are correct.

C.3.3 Notes

C.3.3.1 *Current state-of-the-art*

- Extreme wave conditions are difficult to define. Tests are often performed with 100-year wave or wave environment that developers identify as particularly harmful to their device
- Water current and wind is not considered at this point. For some (but likely not all) devices, these effects may be important.
- Instrumentation of critical systems and/or failure points. Detailed measurements (e.g. pressure distributions) are not typically made due to associated cost and complexity.
- Experimental methods developed for oil & gas and shipping industry are heavily leveraged. Little methods development has been performed by the wave industry.
- What are the important experimental design considerations?
 - Important that the mass properties (mass and moments of inertia) are accurately represented in the experimental tests
 - Testing different survival scenarios may require different scale models and/or tests
 - Instrumentation can be problematic for small device scales, as the required instrumentation may effect inertial properties
- Need to think about what the purpose of experimental tests are before the tests are performed. Need to ask, what do we want to measure/validate/verify. Then a test plan should be developed. This type of systematic approach is not always the standard in the WEC industry.
- Real-time processing of data is important.
 - Real-time data analysis should be performed during the experiments
 - Data processing ensures the results are useful
 - Simulations should also be run real time to find numerical model and experimental test problems so they can be addressed while in the tank – this is not possible after testing has been completed.
- Video is important
- Some redundant measurements make sense given the expense of tank testing

C.3.3.2 Gaps

- Small scale is desirable for Froude scaling/tank limitations, but makes PTO modeling difficult and causes problems with Reynolds number not scaling properly.
- Model PTO systems are not typically repeatable → needs more attention and electronic PTO systems show promise.
- Effective ways to test different failure modes in tank tests – consider when designing tank test program test conditions where there are PTO failures / test when PTO is operational, but grid connection is lost, i.e. fault conditions / what happens if device does not go into “survival mode” during survival condition
- How to identify failure modes and conditions that cause them (i.e. limit states for the system) – well defined for oil & gas, but not yet for WECs
- Test fault conditions
- Developers have traditionally used focused waves to test extreme conditions performance of device. This is not best practice and a response base analysis (i.e. determination of what wave trains cause the largest loads) should be used
- Calibration of wave tanks is critical and not all tanks are well calibrated – especially the low budget tanks that are typically used by smaller developers (which is a larger percentage of the wave energy industry). Wave tank characterization includes the characterization of reflections, basin coverage, energy density, etc.
 - Running numerical models at the same time that experimental measurements are performed. Numerical simulations can help identify for existing tanks
 - Testers should always run and check tank with no model present – seems to be standard practice – developers and testers need to account for calibration time when they are developing test plans
- There are other necessary testing conditions – e.g. tow out, dry lift, installation, O&M, mooring installation, arrays, accidents, boat strike. These conditions are not typically considered as seriously as extreme loads that occur after the installation is completed, even though they are just as important.
- Testing deformable devices (AWS, anaconda) is a challenge – relevant when deformations are large enough to radiate waves – also important when deformation is critical to PTO operation due to scaling issues and when the performance of deformable components need to be tested at scale.
- Syncing and data logging – need a “data unifier” for inexpensive tanks – important if you want to look at results real-time – can save post-processing time and make results more useful after testing is complete.
 - Possibly attach data logging requirements to DOE funding for tests?
 - Approval of test plans?
 - More automation in testing could help – sensors must be compatible with measurement systems
 - follow ITTC procedures
- Difficult to measure pressure distributions for numerical validation – point measurements are standard, spatially resolved measurements are a more “research-level” topic and are typically very expensive

- Material scaling is typically not considered at model scale → loads are passed to FEA/structural software for more detailed analysis
- Small scale tanks (~100K) – there is a company that makes one of these – the cost of tank testing is mostly the experts required to run the tests/setup instrumentation

C.3.3.3 What are the next steps?

- Develop a U.S. (likely DOE) program similar to MARINET (<http://www.fp7-MARINET.eu/>). Critical components of this program would be:
 - Access to wave tanks
 - Characterization of wave tanks prior to testing
 - Reflections
 - Directional waves
 - Basin coverage – i.e. where are the “dead spots” and what is the energy distribution
 - Technical/engineering support for test planning, **model construction**, mooring system, PTO system development, and post-processing – move responsibility for model construction away from developers/testers towards tanks – important that testing center is involved with the design and fabrication of the test model – models should be built with the test facility in mind – approval of test plan/model design
 - Require publication in peer-reviewed conference/journals so that the tank testing is not just a “box checking” exercise
 - Explore possibilities of requiring numerical modeling prior to wave tank testing
 - relevant to do before going into the tank to check for design problems
 - should be performed by a third party to verify design specifications
 - can help develop experimental test plan
 - leverage DOE/National Lab computing facilities
 - Example test programs to represent some set of likely deployment locations – these guidelines would include extreme seas
 - Requirements/test plan should reflect the level of development/cost of the device and test
 - Give priority to developers who ‘need’ the test
- Testing guidelines – consolidate existing guidelines – e.g. ITTC
 - Require that tests follow guidelines or provide rational/justification for not following guidelines
 - Example test programs (super program and everyone tests a subset)
 - Recommended test conditions to cause extreme loading – require to be simulated numerically before it is tested experimentally
 - Require several different extreme conditions to be considered – e.g. short steep waves, long waves, etc
 - Having a reviewed and approved test plan is perhaps better than requiring developers to exactly follow ITTC standards – by DOE determined group (e.g. DVN-GL/National Labs/testing facilities)

- Development of generic PTO systems (e.g. linear rotary) that enable the testing of scale devices – this is challenging because there is very little convergence within the industry
 - Important because friction is a big problem at model scale – very relevant to a U.S. MARINET program
 - Important to do bench-top testing of PTO / dynamic calibrations to determine response – is it linear, non-linear, etc. – complete before test
 - PLC development that can be used with different motors
- Develop methods to experimentally recreate wave trains that are appropriate to replicate realistic extreme sea states (met-ocean breakout group will look into this in more detail)
- Open-source data processing tools for making sense of raw data
 - Some useful tools exist – DIWASP, WAFO
- Ability to easily model non-linear waves in wave tank tests

C.3.3.4 What tanks can be used for ECM testing?

- University of Maine (coming soon)
- OSU
- Carderock
- MARIN
- ECN
- And many others depending on acceptable scale

C.4 Design Standards and Extreme Loading Conditions

C.4.1 Participants

The participants in the Design Standards and Extreme Loading Conditions breakout group are listed below:

Participant	Organization
Jochem Weber (moderator)	National Renewable Energy Laboratory
Jarett Goldsmith	DNV-GL
Yi-Hsiang Yu	National Renewable Energy Laboratory
Diana Bull (note-taker)	Sandia National Laboratories
Gaizka Zarraonandia	DNV-GL
Arnie Fontaine	Penn State ARL
Marco Masciola	ABS

C.4.2 Key Findings and Recommendations

C.4.2.1 Key findings

- **No standards exist:** Although there are guidelines (DNV OSS 312, Equimar, and Carbon Trust), applicable standards, and experience from offshore wind, naval architecture, and oil & gas, there are no dedicated standards for WEC design, particularly for extreme conditions. Wave energy developers often use offshore oil & gas standards as a starting point.

- **Failure modes effects analysis (FMEA):** Not every WEC developer had conducted a detailed FMEA analysis and identified extreme/ultimate limit states for their design during the development process.
- **Lack of data/experience.** The WEC industry is at the nascent stage. Only a limited number of WEC devices have been deployed and tested in the water. The WEC community lacks data, including WEC system information, detailed environmental conditions, structural loads and associated conditions, failures and root causes, overall experience and safety factors used.
- **Uncertainty in determining extreme loading conditions:** WEC developers often face the question of how to estimate the extreme loading conditions, which can be different for different WEC devices and different device components. It is challenging to identify the extreme conditions, which can be extreme sea states or a sequence of operational waves with relatively large amplitudes. In addition, numerical/experimental methods may still result in high uncertainty, including scaling issues, appropriate representation of all coupled systems, and the limitation of methods to represent accidental/survival/temporary conditions.

C.4.2.2 Recommendations

- **Develop design standards:** Currently, DNV and other certifying bodies are working to develop guidelines and the development of standards, and the IEC is working on the draft of a design requirements document. A risk-based approach has been suggested and the standards development will also rely on other industry experience where applicable (e.g. particular systems, subsystems for the WEC devices).
- **Use a risk-based approach for design standards:** One key difference between WECs and other offshore structures is that the risks (loss of investment, loss of life, environmental impact) associated with the failure of a WEC are much less than for most offshore structures (with the notable exception of offshore wind turbines) and ships. A risk-based design approach is suggested, which evaluates the design, impact, and failure probability of the device components relative to the cost. The steps include defining modes of operation, technology assessment, and FMEA analysis and specification of design load cases. For the design standard development, the interim goal is to lead to a “Statement of Feasibility” and the final goal is to use for certification.
- **Share WEC industry data and experience.** To gather more data from all the WEC testing projects, it is essential to ensure all prototypes are instrumented to capture detailed environmental condition and load data and give the WEC developer access to resources in modeling and testing (e.g. access to expertise/computing resources/basins). The MARINET project is a successful example, and Joint Industry Projects (JIPs) are also an option. Test centers and the leasing agency (Bureau of Ocean Energy Management) can play an essential role in pushing for data and experience sharing in the WEC community.
- **Improve met-ocean/extreme sea state, numerical and physical modeling:** See Appendix C.2

C.4.3 Notes

C.4.3.1 Design Standards

- What are the existing standards and are they relevant to the WEC industry?

- No standards exist, although IEC TC114 is in the process of developing a set of wave and tidal device standards. There are guidelines: DNV OSS 312, Equimar, Carbon Trust, applicable standards and experience from offshore wind and oil & gas, (shipping)
- Risk-based approach is applied
 - Defining modes of operation
 - Technology assessment and failure mode identification
 - Specification of design load cases
 - Interim goal: To lead to “Statement of Feasibility”
 - Final goal: Certification of compliance
- Are there gaps in the existing standards?
 - Yes, lots. The whole approach is different to a traditional standards approach.
- Scope of design basis
 - Deployment met-ocean conditions
 - Modes of operation
 - Configuration of all systems
 - System specifications
 - Structural
 - Mechanical
 - Electrical
- Can the developers be provided with advice when best to start the process?
 - Roughly when the developer plans for sea going tests and will undertake relevant and same design tank testing campaign for this sea going campaign
 - Specifically when they can provide all the information required for the establishment of the design basis
 - Certification is not compulsory
 - To ensure best practices & reduce risk.
- Is there need for additional standards development?
 - Yes, but the diversity of WECs requires a flexible approach
 - Many load cases need to be considered: Thousands
 - Baseline safety factors need to be derived for specific cases and risks
 - Gap to be filled: Collection of data to help determine safety factors.
- How does the topic relate to other breakout groups?
 - What are the critical design load conditions (DLCs), including identification of extreme loads?
 - Key survival conditions may not be associated with extreme wave events
 - Well-defined met-ocean characterization needed
 - Understanding of uncertainty from met-ocean characterization, physical modeling, and numerical modeling methods applied
 - Physical understanding of key risks and consequences for each WEC device (FMEA)
 - Once design basis and DLCs are known (i.e. from FMEA), appropriate numerical/physical modeling techniques need to be applied
 - The certification process can help developer progress through design, including reliability and survivability considerations.

- How can standards be written for an industry that has not converged on a winning design archetype?
 - Risk-based approach (e.g. DNV OSS 312) can be used.
 - Rely on other industry experience where applicable (e.g. particular systems, subsystems)
- Is the work being performed by IEC TC 114 on target?
 - The 62600-2 Design Requirements document is still being drafted (unknown if 'on target')
 - IEC TC 114 is discussing this risk-based approach as the appropriate way to go forward.
- How should the standard development community work to best help the WEC industry and vice versa?
 - Lack of data is a problem. WEC industry needs to share their experience.
 - WEC industry can help by providing data.
 - WEC system information, detailed environmental conditions, structural loads and associated conditions, failures and root causes, overall experience and safety factors used

C.4.3.2 Identification of Extreme Loading Conditions

- How is the WEC industry currently identifying conditions where extreme device loading occurs?
 - Each developer has their own processes
 - Often using offshore oil & gas standards (as starting point, or as sole source of environmental condition recommendations)
 - Identification of conditions through experimental (often) and numerical modeling campaigns
 - Careful application of techniques (see other groups), and awareness of limitations is critical
- What gaps in existing methods are holding the industry back?
 - Not everyone is identifying extreme/ultimate limit states through FMEA (risk assessments) – Living document.
 - Numerical/experimental methods may still result in high uncertainty
 - Scaling issues
 - Appropriate representation of all coupled systems
 - Representation of sea states in physical modeling
 - Limitation of test basins/measurement instrumentation
 - Limitation of numerical methods to represent accidental/survival/temporary conditions
 - Validation of numerical models
 - Not everyone has well-defined test plans or follow them
- What research could help address these gaps?
 - Training in risk-based design approaches
 - E.g. example of detailed FMECAs (applied to reference model or publically known design)

- Ensure all prototypes are instrumented to capture detailed environmental condition and load data
 - Including full-scale deployments
 - Role of test centers and leasing agency (BOEM)
- Giving access to resources in modeling and testing (e.g. access to expertise/computing resources/basins) – MARINET model
 - But need to consider sharing of data
- Joint Industry Projects (JIPs) and sharing of data
- Under what conditions do WECs experience extreme loads?
 - Depends on each individual WEC
 - Potential for some similarities/trends (particularly among similar WEC types)
 - E.g. connection points, end stops, resonance, system memory or time accumulated effects, breaking wave impacts, high accelerations, steep high frequency waves, tow out, installation, directionality issues, superposition of different environmental conditions, slap/slam, green water.
 - Potential to learn from other industries (e.g. moorings loads)
- What type of numerical and experimental methods can be used to model devices under the different type of extreme loading conditions?
 - Experimental: See other Experimental group
 - Numerical: See other Numerical group

Appendix D Post-Workshop Questionnaire Responses

Following the workshop, attendees were encouraged to fill out the online questionnaire presented in the Figure D-1. Table D-1 presents the attendees responses to the questions. Note that the responses are anonymized.

Extreme Conditions Modeling Workshop Post-Workshop Questionnaire

For reference, the objectives of the ECM workshop are presented below.

Objectives:

- * Review the state-of-the-art experimental and numerical modeling methods for predicting device loads and motions in extreme conditions
- * Identify gaps in the current modeling methods
- * Identify research pathways to most effectively advance ECM modeling methods

Name

Please enter your name (not required)

Workshop Value

How valuable did you find the workshop?

- ☐ Very valuable
- ☐ Valuable
- ☐ Moderately valuable
- ☐ Not valuable

Other comments on workshop value and/or success.

Overall Workshop Conclusions

Please summarize what you feel were the major conclusions of the workshop.

Breakout Session Conclusions

What breakout session did you attend?

- ☐ Numerical Modeling
- ☐ Physical Model Testing
- ☐ Sea State Characterization
- ☐ Design Standards and Identification of Extreme Loading Conditions

What were the major conclusions from your session?

Recommended Path Forward

What research and/or resources are most needed by the WEC industry in the area of extreme conditions design and modeling?

Future Workshops

Do you have any suggestions on how to improve future workshops of this type?

Never submit passwords through Google Forms.

Figure D-1. Post-workshop questionnaire that attendees were asked to complete.

Table D-1. Response to the post-workshop questionnaire.

	Please summarize what you feel where the major conclusions of the workshop.
Response 1	There is still a lot too be done, and technology developers still need a lot of help!
Response 2	<ul style="list-style-type: none"> - Extreme WEC conditions not confined to extreme wave conditions - Low fidelity numerical models (e.g. linear frequency and semi non-linear time domain models) often incapable of representing extreme conditions - High fidelity numerical models (CFD) are often as costly as tank testing. Furthermore, it is likely that they will need to be verified against model measured in tank. - Numerical modelling offers more complete simulations as it is not subject to instrumentation limitations (pressure distributions, PTO simulation). <p>Numerical and physical models should be developed in a complementary fashion.</p> <p>Identification of extreme wave conditions from MetOcean data by extrapolation of probability distribution (Weibull) may underestimate extreme conditions.</p>
Response 3	<ul style="list-style-type: none"> * standardization of design for survival of WECs is difficult as there is such a wide variety of devices * modeling tools, appropriate for extreme condtions / response, that balance accuracy and speed/cost, are not necessarily available. a hybrid approach where mid and high fidelity tools are used may be necessary * the data/tools necessary for accurate, site specific extreme conditions estimations are not necessarily available
Response 4	<ul style="list-style-type: none"> - There is considerable amount of work to be done in this field. - Experience and knowledge can be imported from other ocean engineering fields yet must be tailored for the wave energy industry. - Additional measurements and measurement capabilities to determine the true distribution of extreme wave events are required. - There are numerical tools at the disposal of researchers, yet a detailed description and independent analysis of each is vital to efficient use to time and resources.

Response 5	<ul style="list-style-type: none"> - Extreme behaviour/conditions are technology dependent. Need to be identified by developer first. - End stops are critical regarding survivability of WECs. Should be avoided whenever possible. End stops may be showstoppers actually. - US MARINET like project sounds like a great idea, however issues identified with the EU MARINET needs to be addressed. - CFD is not a practical option for WEC developers. CFD needs experts for correct use. Developers do not have the required resources.
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	What breakout session did you attend and what were the major conclusions from your session?
Response 1	Physical Model Testing: Need to create a system in the US similar to the mariner project in Europe to help small companies develop their ideas technically better before going to the prototype stage. Additionally to lab time, giving those companies support time from expert engineering companies on modeling would be a good thing.
Response 2	Physical Model Testing: -A Marinet style framework in the US to assist developers in the successful implementation of tank test campaigns. - While standards and recommended practices exist for tank testing WECs, they have not been adopted. This should be encouraged. PTO simulation is very difficult to implement in physical model tests. A generic PTO simulator would be ideal. However, given the wide range of WEC configurations, A truly generic solution may not be feasible.
Response 3	Numerical Modeling: * modeling tools, appropriate for extreme conditions / response, that balance accuracy and speed/cost, are not necessarily available. a hybrid approach where mid and high fidelity tools are used may be necessary * CFD tools may be used judiciously to support a robust modeling program
Response 4	Sea State Characterization: Reported in the break-out group notes.
Response 5	Numerical Modeling, Physical Model Testing: - CFD is not a practical option for WEC developers. CFD needs experts for correct use. Developers do not have the required resources (people and computational resources) - US MARINET like project sounds like a great idea, however issues identified with the EU MARINET needs to be addressed.
Response 6	Sea State Characterization

	What research and/or resources are most needed by the WEC industry in the area of extreme conditions design and modeling?
Response 1	Funding, and dissemination of know how.
Response 2	<p>1. Developer access to tank facilities</p> <p>2. Assistance in the development of physical models (instrumentation, PTO simulation)</p> <p>3. Reduction in cost of high fidelity numerical modelling tools ... or improvement in fidelity of low cost numerical modelling tools!</p>
Response 3	<p>* evaluation and bench marking of available numerical modeling packages for a variety of WEC types in extreme conditions / response</p> <p>* methodology for identifying conditions (and instances) resulting in potential failure</p>
Response 4	<p>- Better ability to determine the true distribution of extreme wave events for each geographic locations.</p> <p>- A quantitative understanding of the risks WEC developers are willing to undertake in order to minimize the costs of designing for 100/500/1000 year events.</p>
Response 5	<p>- Access to experimental facilities and numerical resources.</p> <p>- Access to expertise to make good use of these resources.</p>

	Do you have any suggestions on how to improve future workshops of this type?
Response 1	Well let see if the workshop has any impact on DOE, if it does, we ought to have more.
Response 2	<p>This workshop (like many others in this field) was dominated by representatives from research institutions, with only three representatives from WEC developers (Pelamis, Columbia Power, and RME).</p> <p>In addressing the conclusions drawn by this workshop (particularly the development of a Marinet style project) success will require a more balanced approach between those on the supply side (research institutions, tank facilities) and those on the demand side (developers).</p> <p>Having said this, it seems that the three developers in attendance were given precedence as they were each invited to give presentations at the start of the workshop. Perhaps the poor representation of developers was due to unwillingness on their part to engage?</p>
Response 3	a little more time, and a little more focus (ie reining in of wandering conversations)

Response 4	<ul style="list-style-type: none"> - Excellent conference in general. - An additional workshop to disseminate the findings from each group. <p>There was considerable need to understand the events taking place in other groups in order to determine the best path forward to your group. All "break-out" groups are connected and information flow is important.</p>
Response 5	It was all very good. Maybe it would have been better to engage more WEC developers, or to survey what they believe are their issues prior to the workshop.
	How valuable did you find the workshop?
Response 1	Very valuable
Response 2	Valuable
Response 3	Valuable
Response 4	Very valuable
Response 5	Very valuable
Response 6	Valuable

	Other comments on workshop value and/or success.
Response 1	<p>Good to bring people from the various part of the industry, and discipline together, only something good can come out of that..</p> <p>I feel that some of the recommendations to DOE that cam out of the conclusions are very good and hope they can be implemented</p>
Response 2	The format of this workshop made for very productive discussion as there was a good mix of presentation and discussion. Workshops dominated by presentations often risk isolating the majority of the participants, while those dominated by discussion may descend into long unstructured rambling! This workshop's mix of these two elements made for a very efficient format.
Response 3	it was a huge topic, perhaps one additional day would have been beneficial