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Ocean Power Technologies PowerBuoy®:

System-level Design, Development and Validation Methodology

OMAE 2014

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Outline

Objective: Window into design approach at a WEC company

- Describe the product (PowerBuoy)
  - Aspects that design must consider
- Design approach
  - Structure
  - Power Takeoff (PTO)
- Examples drawn from past projects

Company Overview

Commenced Operations:	1994
Incorporation:	Delaware, USA
Operating Locations:	Pennington, NJ, USA; Warwick, UK; Melbourne, Australia
Total Employees:	30
Intellectual Property:	68 US patents issued or pending
Cash and Investments:	$19.6 million (as of January 31, 2014)
Public Listing:	Nasdaq (OPTT)
Company Focus:	Design, manufacture, sell systems to generate power from ocean waves
Project Locations:	North America, Europe, Japan, Australia

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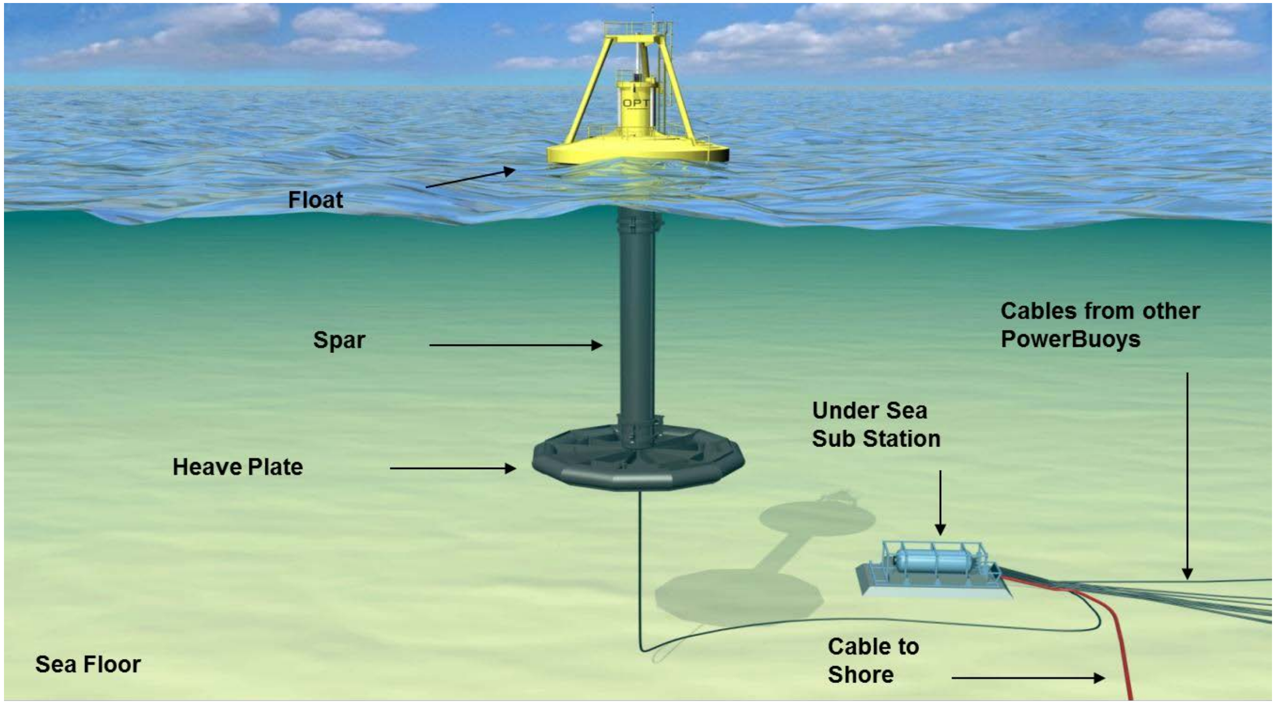
PowerBuoy Description

- Moored system
- Float moves vertically along spar; relative motion drives thrust rod to rack and pinion system. Generator rotates, creating power.
- Power delivered to local payload (“autonomous”) or to grid (“utility”)



Schematic of PowerBuoy for utility project. Compliant mooring not shown.

Stages of Design Process

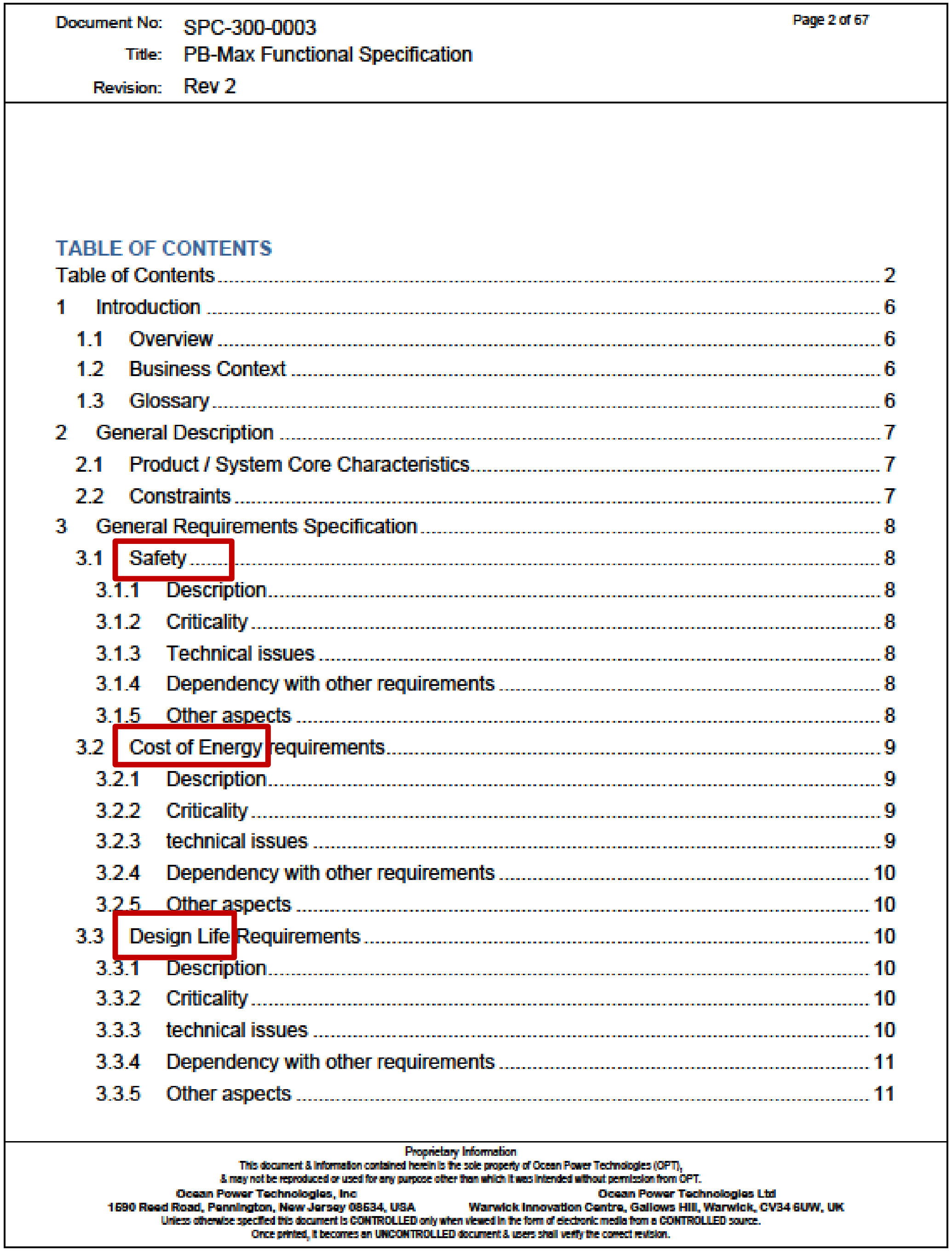
- Define requirements
- Structure design
  - Concept generation and evaluation
  - Wave tank testing of concepts
  - Down-selection of concepts
- PTO design
  - Concept generation and evaluation
  - Component and subsystem testing

These steps will be illustrated with examples from projects a couple projects that were funded by DOE and internal funding in the following slides

Requirements

- Requirement source
  - Customer generated: preferred but not always possible
  - Internally generated: customer feedback, market research, past experience
- Information included in requirements
  - Performance targets
    - Output power, efficiency, operating voltages and currents, mechanical and electrical interfaces, data monitoring and acquisition
  - Cost targets
    - Define cost metrics
    - Estimate capital and operational costs
  - Physical parameters
    - Weight, volume, transportation considerations
  - Site conditions
    - MetOcean: wave climate, survival conditions, water depth, seabed slope and type
    - Logistics: Deployment, on-site maintenance and support, recovery for service
  - System functions
    - Mechanical
    - Electrical

Example Requirements Document



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Title: PB-Max Functional Specification
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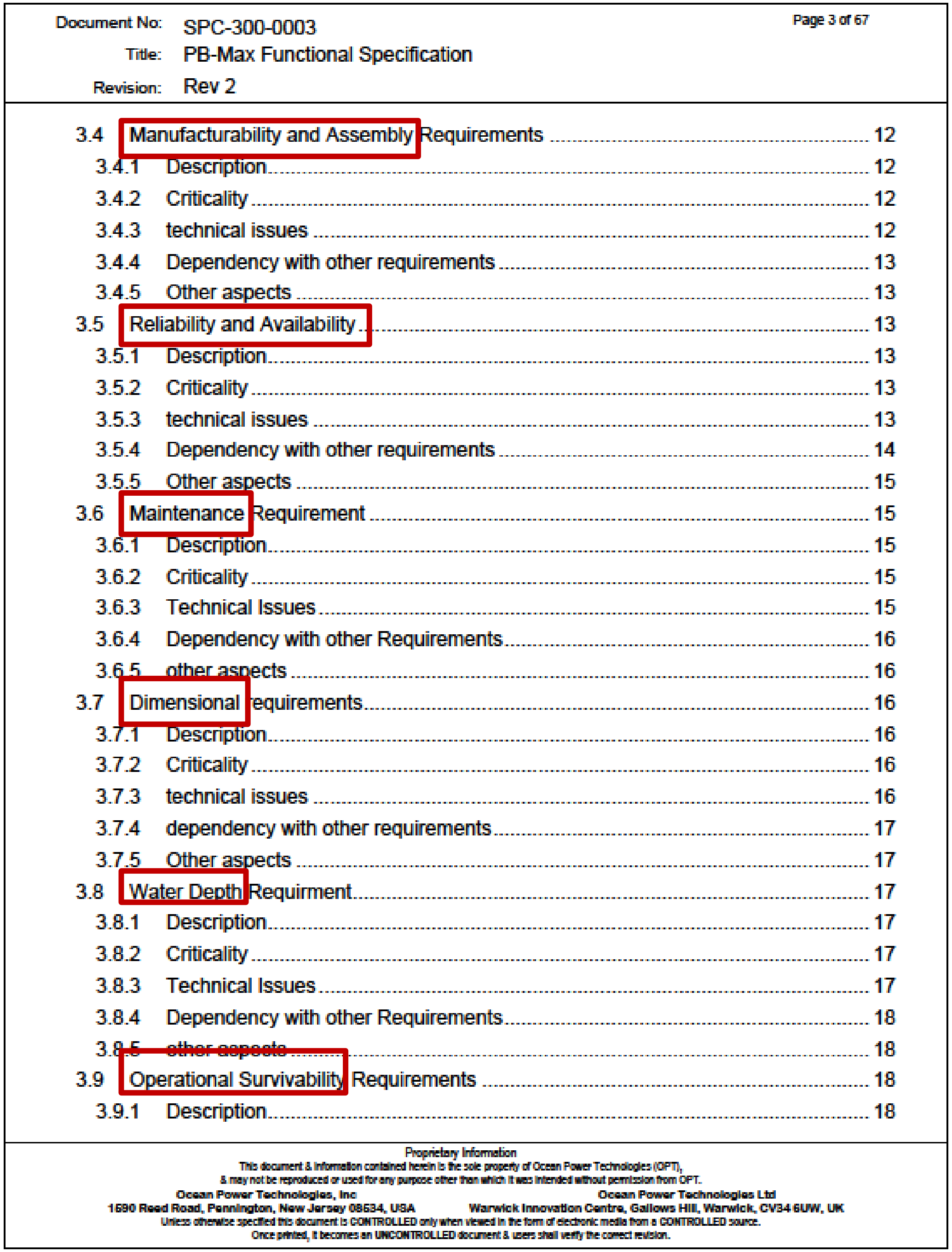

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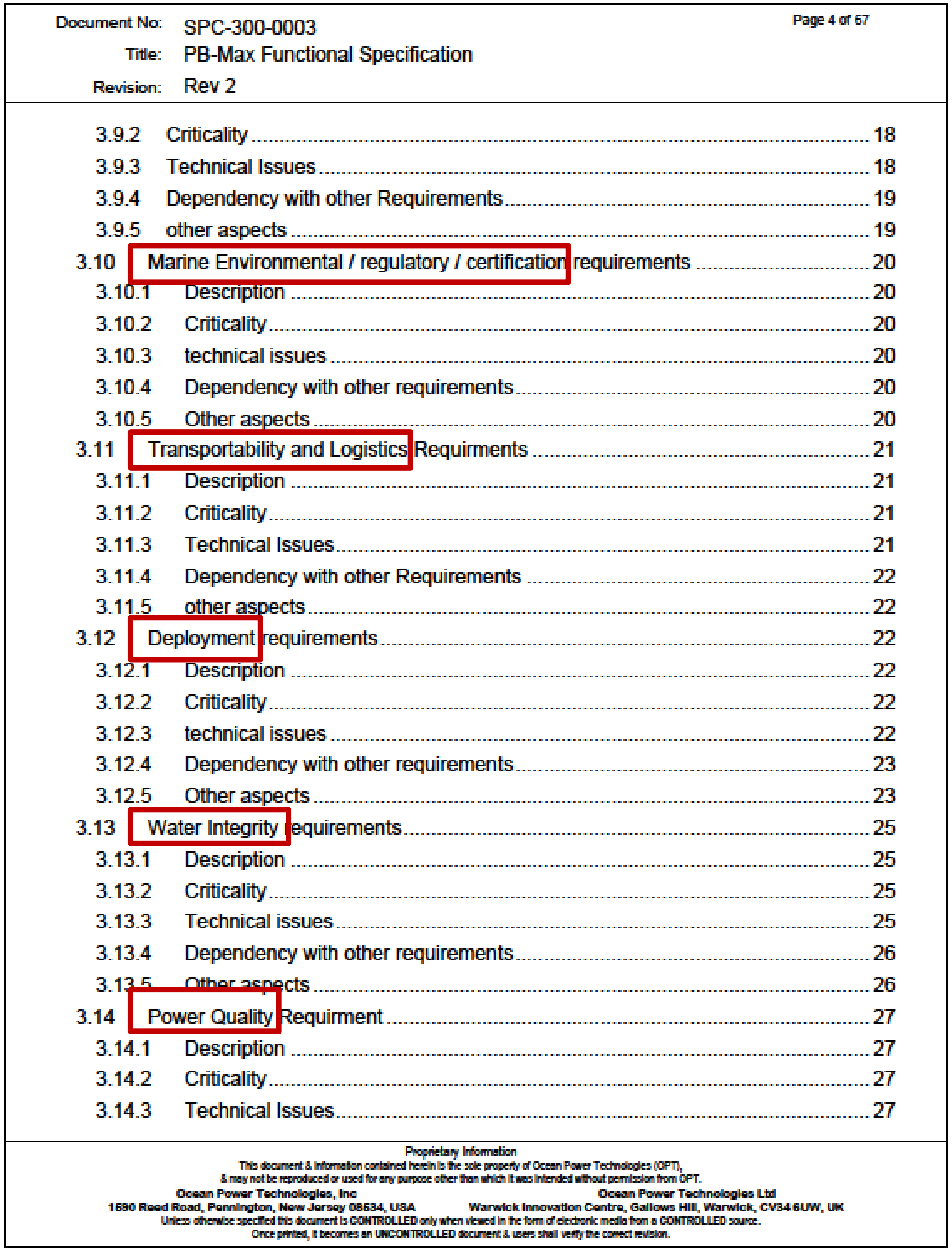

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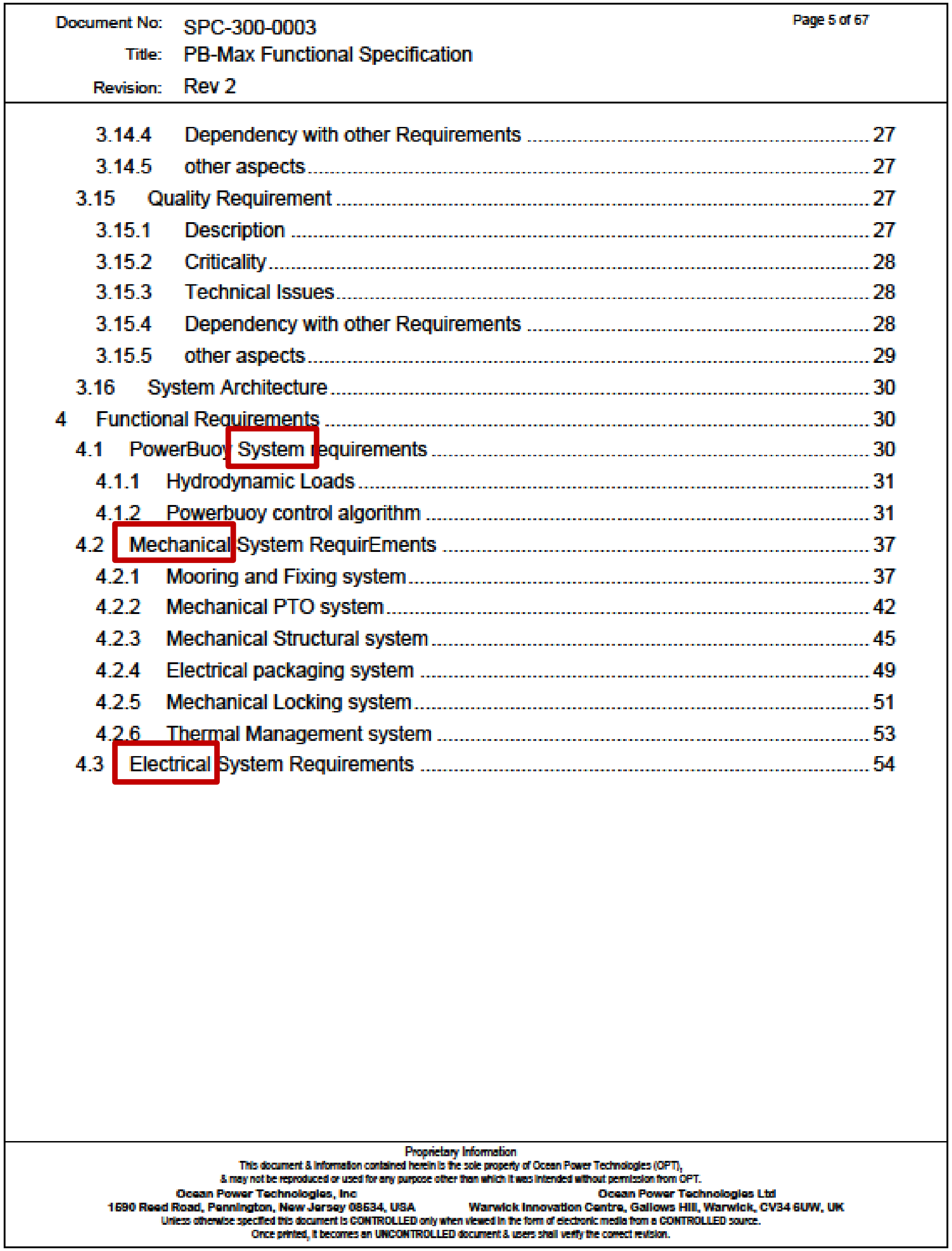

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Structure Design Overview

- Concept generation and evaluation
- Wave tank testing of concepts
- Down-selection of concepts

Structure: Concept Generation and Evaluation

Example tradeoff of 3 floats and 3 moorings

- Down-selected from wider range of geometries
  - Frequency domain modeling
- Concepts compared based on power output and loads
- Analysis tools
  - Simulations performed with OrcaFlex and/or in-house code (time domain modeling, Matlab)
  - Survival and operational wave tank tests (2 rounds)

		Float		
		Symmetric	**Cylinder w/Plate**	**Rhombus**
Mooring	**Monopile**	Compare: * Float power performance * Float load shedding vs. draft * Mooring and float loads * Mooring power performance		
	Gimbal			
	Tension Leg Platform			

Initial conceptual PowerBuoy configurations

Structure: Initial Concept Evaluation using Model Tools

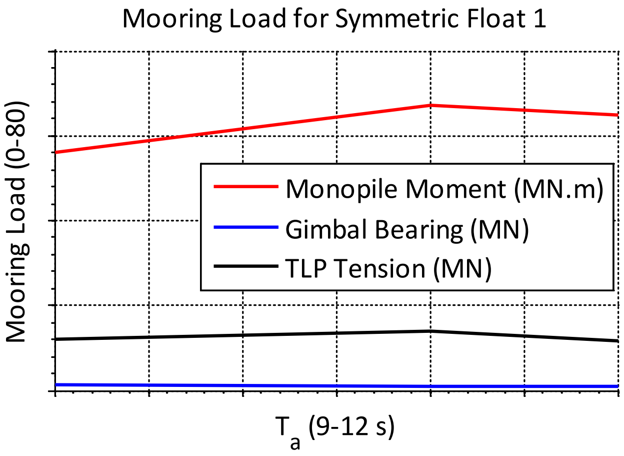
For Different Floats, Power Prediction (kW) vs. Sea State

		Symmetric					Cylinder w/Plate					Rhombus				
H_s (m)	5.5				500-600	420-500				750-1000	510-600				550-750	550-750
	3.5			180-270		120-210			380-470		200-210			280-370		180-210
	2			50-100					150-160					80-140		
	1	5-30	5-30	5-30			15-55	15-55	30-40			5-30	5-30	5-30		
		5	**6**	**7**	**9**	**12**	**5**	**6**	**7**	**9**	**12**	**5**	**6**	**7**	**9**	**12**
		T_a (s)					T_a (s)					T_a (s)				

For Different Floats, Annual Average Power Prediction (kW) at 3 Deployment Sites

	Float		
	Symmetric	Cylinder w/Plate	Rhombus
Site A	40-90	90-140	110-160
Site B	70-120	90-140	130-180
Site C	90-140	120-190	180-250

Example Survival Load Simulations at Different Wave Periods


Mooring Load for Symmetric Float 1

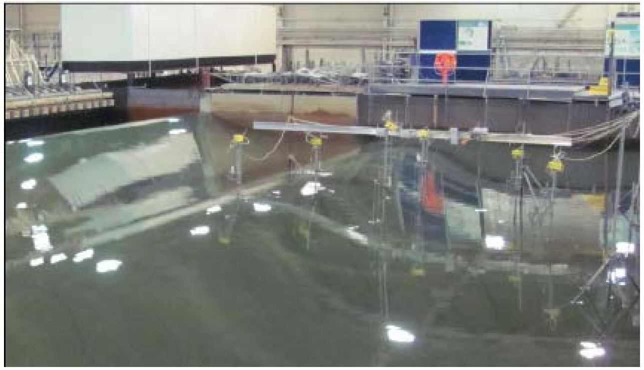
Structure: Concept Evaluation using Wave Tank Tests

Test Activities

	Test Type	
	Survival	**Operational**
Test 1	3 Floats 3 Moorings 3 Drafts	3 Floats 3 Moorings 3 Drafts
Test 2	4 Floats 1 Mooring 1 Draft	
Test 3		2 Floats 1 Mooring 2 Controls

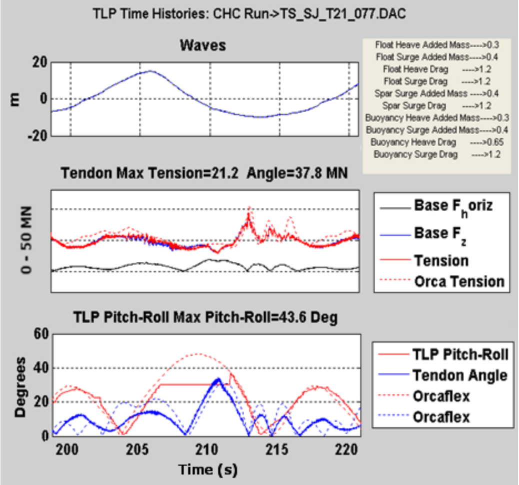
Operational Test: Model Installation

Survival Test: Wave Calibration

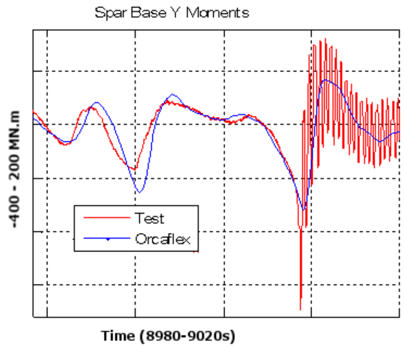


- Operational tests
  - Evaluate power performance, fatigue
  - Tune hydrodynamic coefficients
- Survival tests
  - Estimate design loads
  - Tune hydrodynamic coefficients
- Tuned simulations used for post-test analysis

Simulation with Test-Tuned Coefficients

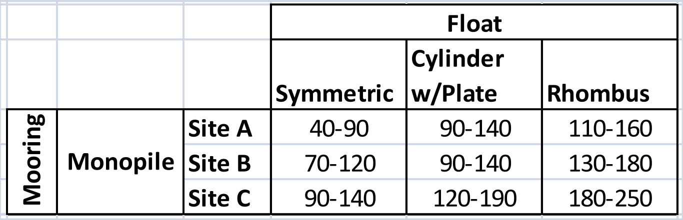


Example Simulation Evaluation



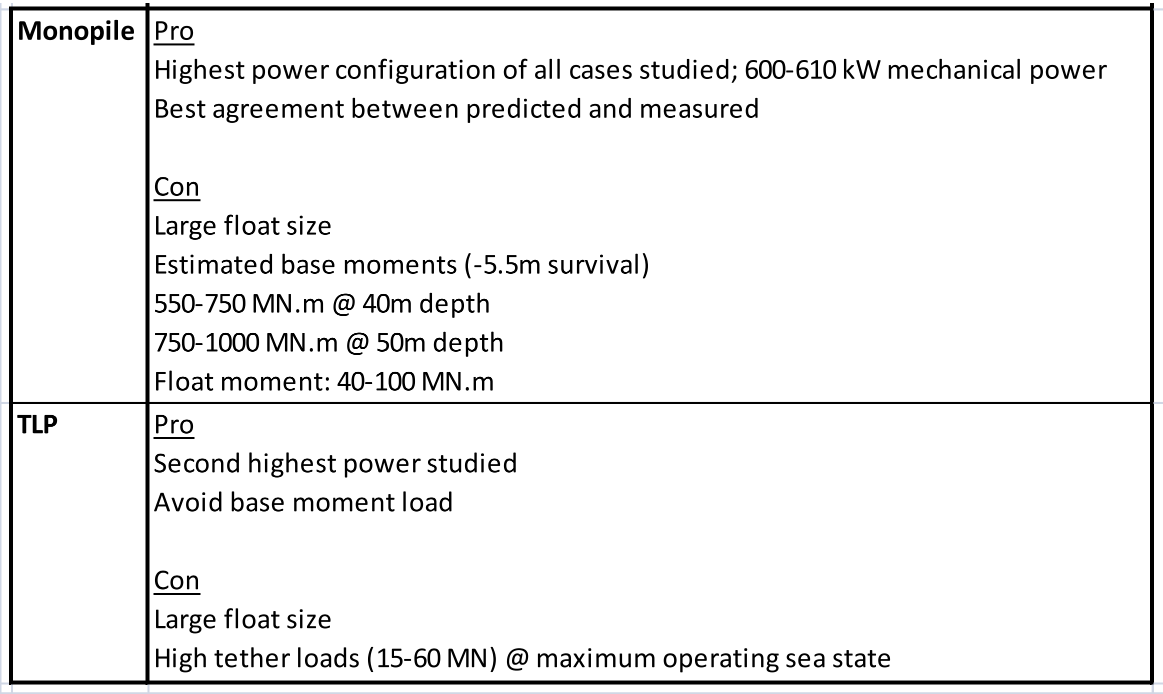
Structure: Down-Selection of Concepts

- Compare floats
  - Highest power for Rhombus
- Compare moorings
  - Highest power output for Monopile
  - Lowest loads for Tension Leg Platform
- Final decision then made by management based on these and other considerations (e.g. cost, deployment, customer preference)
- On to next stages of project



			Float		
			Symmetric	Cylinder w/Plate	Rhombus
Mooring	**Monopile**	**Site A**	40-90	90-140	110-160
		Site B	70-120	90-140	130-180
		Site C	90-140	120-190	180-250

Comparison of Moorings



Monopile	Pro Highest power configuration of all cases studied; 600-610 kW mechanical power Best agreement between predicted and measured Con Large float size Estimated base moments (-5.5m survival) 550-750 MN.m @ 40m depth 750-1000 MN.m @ 50m depth Float moment: 40-100 MN.m
TLP	Pro Second highest power studied Avoid base moment load Con Large float size High tether loads (15-60 MN) @ maximum operating sea state

PTO Design Overview

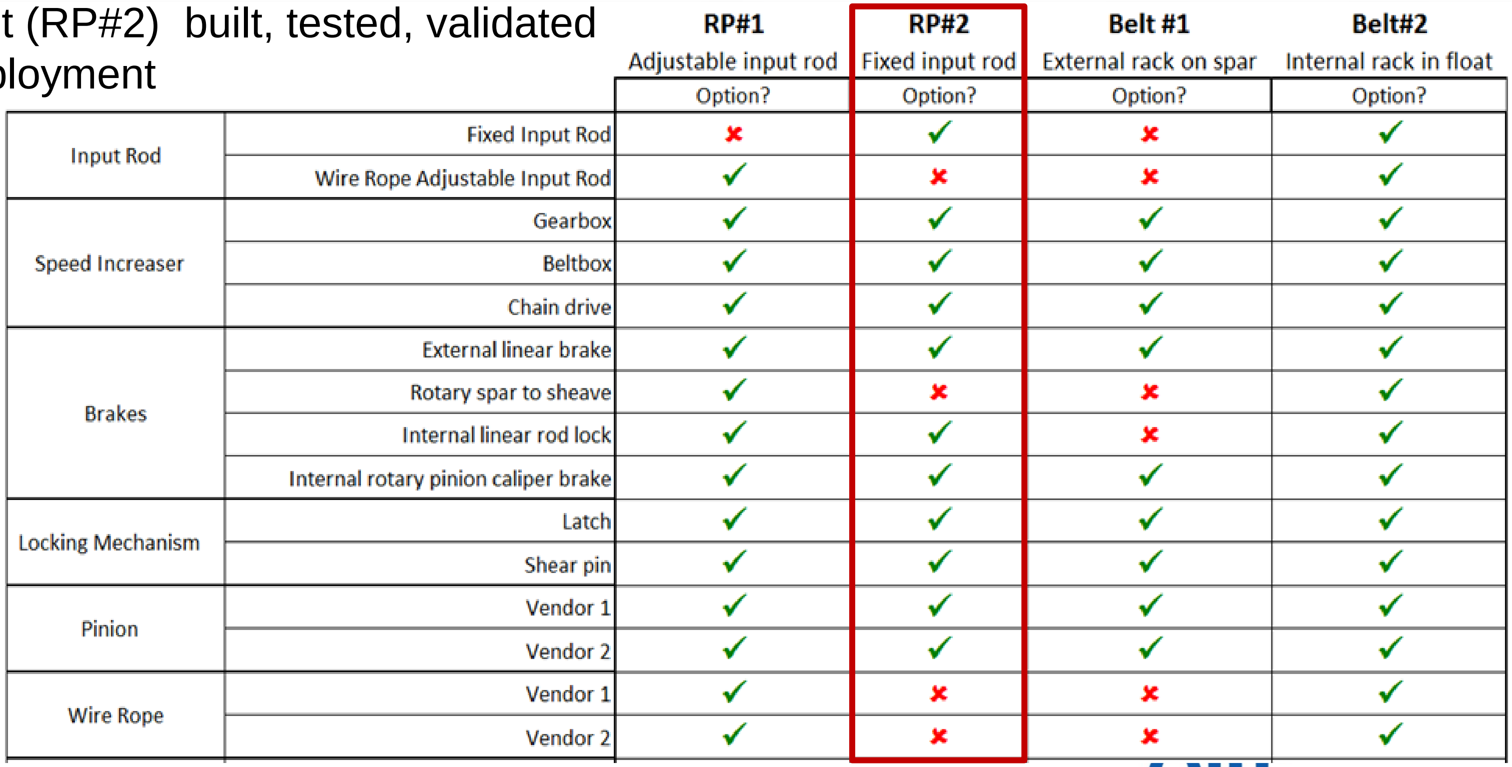
- Concept generation and evaluation
- Component and subsystem testing

PTO: Concept generation and evaluation

Tradeoff: Rack and Pinion vs. Belt Drive

- Table: Compatibility with PTO
- Other criteria (cost, reliability)
- Vendor input on designs; cost quotes

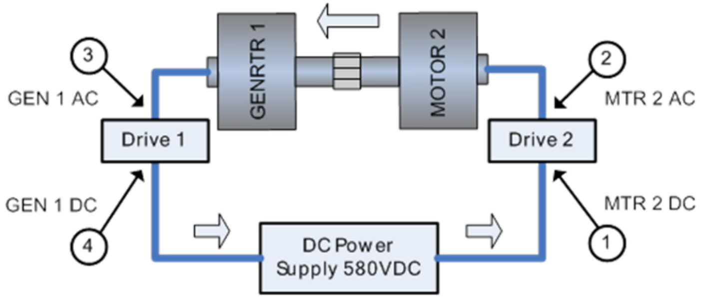
Winning concept (RP#2) built, tested, validated for ocean deployment



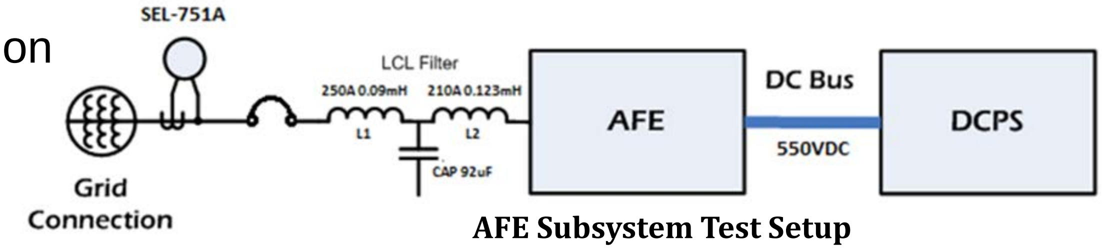
		RP#1 Adjustable input rod Option?	RP#2 Fixed input rod Option?	Belt #1 External rack on spar Option?	Belt#2 Internal rack in float Option?
Input Rod	Fixed Input Rod	✗	✓	✗	✓
	Wire Rope Adjustable Input Rod	✓	✗	✗	✓
Speed Increaser	Gearbox	✓	✓	✓	✓
	Beltbox	✓	✓	✓	✓
	Chain drive	✓	✓	✓	✓
Brakes	External linear brake	✓	✓	✓	✓
	Rotary spar to sheave	✓	✗	✗	✓
	Internal linear rod lock	✓	✓	✗	✓
	Internal rotary pinion caliper brake	✓	✓	✓	✓
Locking Mechanism	Latch	✓	✓	✓	✓
	Shear pin	✓	✓	✓	✓
Pinion	Vendor 1	✓	✓	✓	✓
	Vendor 2	✓	✓	✓	✓
Wire Rope	Vendor 1	✓	✗	✗	✓
	Vendor 2	✓	✗	✗	✓

PTO: Component and Subsystem Testing

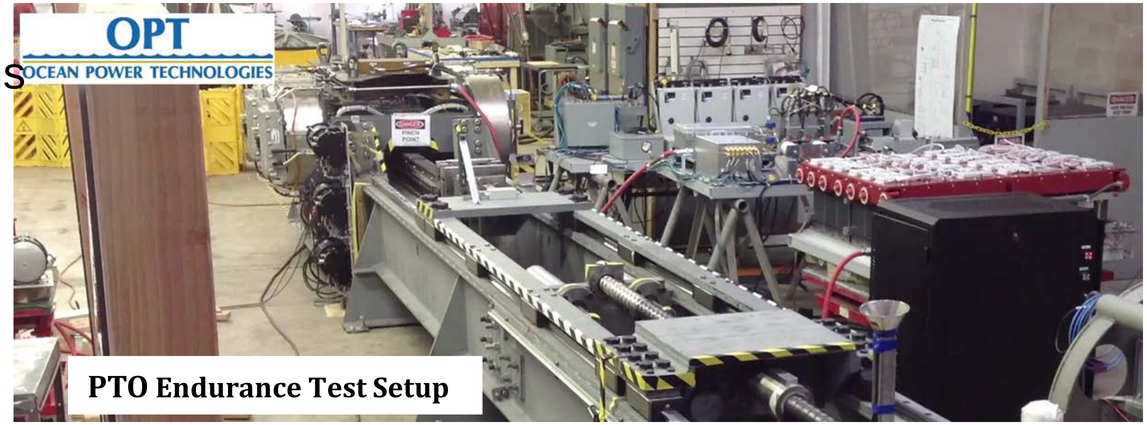
- Generator/drive back-to-back test
  - Measurements: Power, thermal performance, motor constants (Kt, Ke)
- Active Front End (AFE) Inverter test
  - Validate interface between High Voltage DC bus and AC voltage on the Utility grid
  - Validate AFE control setup (precharge, synchronization, bidirectional power transfer)
- PTO endurance test
  - Represent real wave conditions
  - Measure efficiency, vibration
  - Validate control, HMI



Setup For Back-to-back Testing of Generator Drive



AFE Subsystem Test Setup



PTO Endurance Test Setup

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Conclusions

- Goal: Window into design process for wave energy converters
- Reviewed design process; examples from recent project
- Stages of design process
    - Concept generation and evaluation
    - Testing