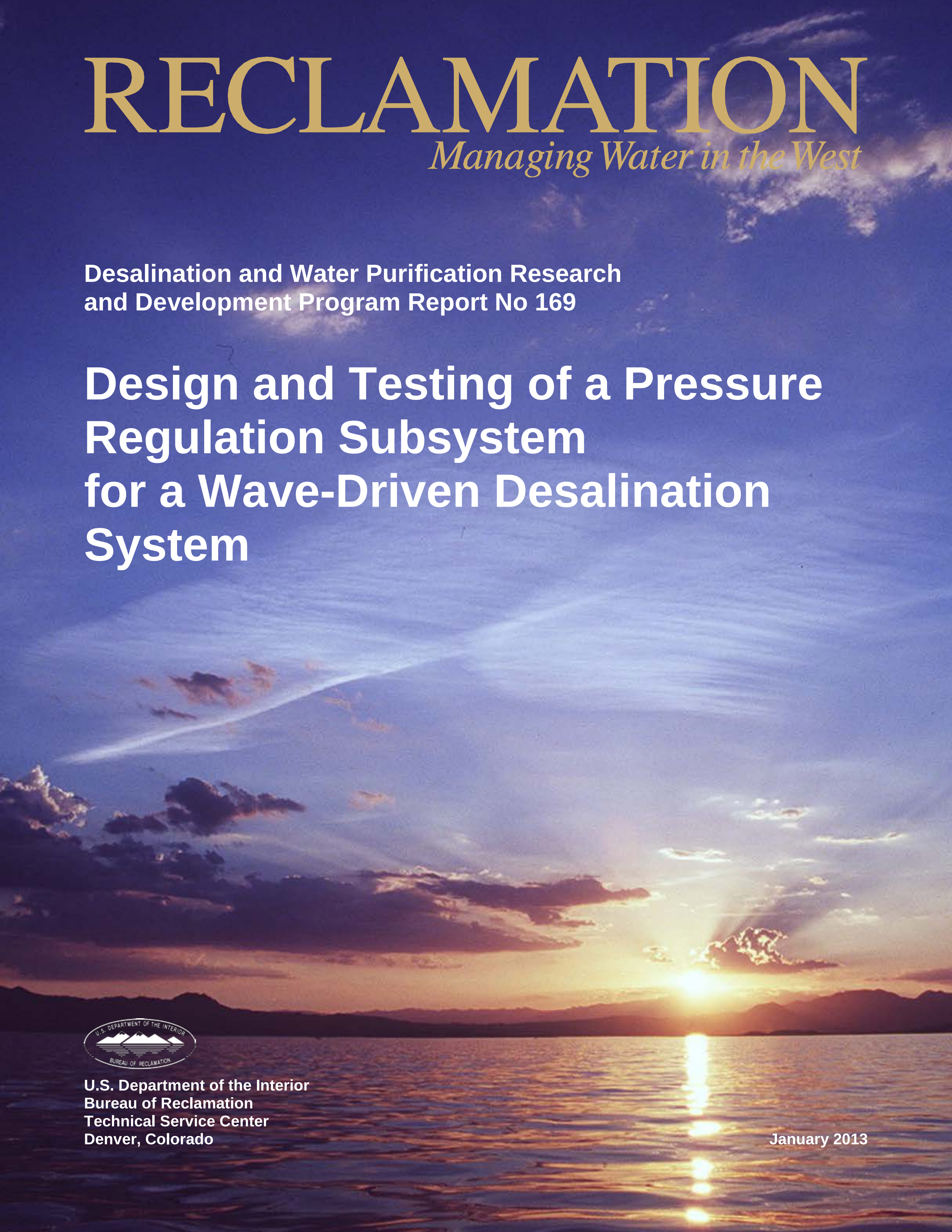

RECLAMATION

Managing Water in the West

Desalination and Water Purification Research and Development Program Report No 169

Design and Testing of a Pressure Regulation Subsystem for a Wave-Driven Desalination System

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

January 2013

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Desalination and Water Purification Research and Development Program Report No. 169

Design and Testing of a Pressure Regulation Subsystem for a Wave-Driven Desalination System

Prepared for the Bureau of Reclamation Under Agreement No. R11AC81538

By

Resolute Marine Energy, Inc

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U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

January 2013

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

The views, analysis, recommendations, and conclusions in this report are those of the authors and do not represent official or unofficial policies or opinions of the United States Government, and the United States takes no position with regard to any findings, conclusions, or recommendations made. As such, mention of trade names or commercial products does not constitute their endorsement by the United States Government.

Acknowledgments

The Desalination and Water Purification Research and Development Program, Reclamation, is the sponsor of the research.

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1. Background

1.1. Project Objective

The objective of this project is to design, build and test a cost-effective pressure and flow-rate regulation subsystem (the "Subsystem") for use in conjunction with seawater reverse osmosis ("SWRO") desalination systems powered by (ocean) wave energy.

The project comprises seven discrete tasks which will be undertaken to ensure success which, at project conclusion, will be measured by the performance of the Subsystem in reference to pre-established Subsystem performance requirements.

1.2. Background

This project will be conducted pursuant to a FOA issued and awarded by the Bureau of Reclamation Desalination and Water Purification Research and Development program (DWPR). The DWPR's stated research priorities for fiscal year 2011 are: *"…integrating desalination with renewable energy sources...,*" and "*…combining renewable power sources and the development of technology suitable for small communities*." This project is highly responsive to these two objectives because it would:

a) Enable standard SWRO desalination technologies to work with a wide range of wave and tidal energy conversion devices

b) Bring an extremely powerful and abundant renewable energy resource to bear on the problem of providing much-need additional fresh water supplies

c) Validate a fresh water production system that will have broad commercial appeal in several markets including island and remote coastal communities, developing countries and military and disaster relief organizations

2. Tasks

2.1. Task 1: Determine Subsystem Requirements in the Context of Customer Requirements for a Fully-Integrated, Wave-Driven SWRO System:

The scope of effort under this task has been to derive the system level requirements of the world's first WEC-driven seawater desalination system (Wave2O™) that operates completely “off-grid” and displaces the sole competitor in this market segment - diesel-driven systems. Target customers are coastal communities and resorts around the world which have critical water shortages, limited or no grid connection, and a nearby energetic wave resource. We estimate our addressable market to be $10 billion per year. Depending on input fuel prices, diesel-powered systems produce water at costs ranging from 1.5x - 6x greater than Wave2O™ and therefore Wave2O™ can compete on a straightforward.

Wave2O™ comprises a proprietary WEC that pressurizes seawater to drive a reverse osmosis (R/O) desalination unit. The R/O unit does not need a connection to an electrical grid and comprises readily available off-the-shelf components connected to an innovative subsystem invented by RME. Competitive advantages of the system include: low capital cost; quick deployment; easy to scale and maintain; minimal environmental impact and water production at competitive cost.

A 25-WEC Wave2O™ system can manufacture approximately 0.65 million m3/year of fresh water (enough to supply 20,000 people); fits in standard marine shipping containers; can be installed in a matter of a few weeks; does not require connection to an electrical grid and can be operated and maintained using local labor. In the case of RME's first customer, a district municipality in South Africa's Kwazulu-Natal region, only 30% of fresh water demand is produced locally so fresh water must be delivered by truck from a great distance and residents must expend an inordinate amount of time and energy procuring their daily water supplies (Figure 1).

Wave Climate	
▪ Average power (deep sea)	20 kW/m
▪ Deep sea to shore losses	30%
▪ Period	6s
▪ Wave height	3 m
▪ Wave train duration	19 h/day
Desalination system	
▪ Step up pump efficiency	75%
▪ Step up turbine efficiency	75%
▪ Energy recovery device	70%
▪ Pressure stabilization system	90%
WEC	
▪ Efficiency	40%
▪ Width	5 m
▪ Replacement rate	10%/year
▪ Manufacturing cost (initial)	$51,200
▪ Hydraulic PTO efficiency	80%
▪ Power rating (mechanical)	28.95 kW
Plant description	
▪ Number WEC for operations	25
▪ Number of additional WEC for continuity	2
▪ Off-shore footprint	2,000 m^2
▪ Small desalination	0
▪ Large desalination	5
▪ Desalination maintenance ratio	10%
▪ Average operation time	18.5h/day
▪ Average daily production	1,789 m3/day
▪ Average daily production per WEC	71.6 m^3/day/WEC
▪ People impacted per plant	21,247

Figure 1. Wave climate.

In addition, the national government is required to subsidize this highly inefficient practice. Purchasing a 25-WEC Wave2O™ system will provide an attractive payback (less than 10 years for our launch customer) and will attract buyers wherever it can produce fresh water at a cost that lowers or eliminates subsidies (Figure 2).

Plant economics	
▪ Method: discounted cash flow	
○ Discount factor	5.5%
○ Lifetime	20 years
○ Terminal value	$0
▪ Number of WEC already installed	250
▪ LCOW without RME profit	$0.97/m³
▪ LCOW with RME profit	$1.44/m³
▪ Payback period for municipalities	10.56 years
Installation costs	
▪ Hardware	
○ To RME	$1.45M
○ To desalination provider	$1.75M
○ To water utility (customer)	$0.55M
▪ Shipping and handling	
○ To RME	$140K
▪ Labor	
○ To RME	$55K
○ To desalination provider	$4K
○ To water utility (customer)	$25K
Recurring costs	
▪ Hardware	
○ To RME	$215K/year
○ To desalination provider	$148K/year
▪ Shipping and handling	
○ To RME	$16K
▪ Labor	
○ To RME	$2K
○ To desalination provider	$3K
○ To water utility (customer)	$55K

Operations and maintenance	
▪ WEC Maintenance period	6 months
▪ Number WEC replaced per maintenance	2
▪ Number of WEC installed per day	3
▪ Number of WEC replaced per day	2
▪ Installation duration	0.6 month
▪ Maintenance duration	4 days
▪ Desalination maintenance period	3 months
Pricing Strategy	
▪ Plant installation	$275,000/WEC
▪ Maintenance premium (of costs)	15%
Revenue and cost breakdown of a 25-WEC plant (M$)	
▪ Revenue:	
▪ Installation	6.9
▪ Operations and maintenance	4
▪ Installation costs to RME	
▪ Desalination system (Hardware)	1.75
▪ Wave Energy Converters (Hardware)	0.97
▪ Shipping and handling	0.14
▪ Labor	0.06
▪ Total costs to RME	2.92
▪ Operations and maintenance costs to RME	
▪ Desalination system (Hardware)	1.95
▪ Wave Energy Converters (Hardware)	1.56
▪ Shipping and handling	0.21
▪ Labor	0.03
▪ Total costs to RME	3.78
▪ Gross Margin over lifetime (20 years)	4.24

Figure 2. WEC Wave2O™ system summary.

As can be seen in the summary chart at the right, a Levelized Cost of Water (LCOW) of $1.44/m^3$ can be achieved at an investment offering the customer a 10-year return on their investment (Figure 3).

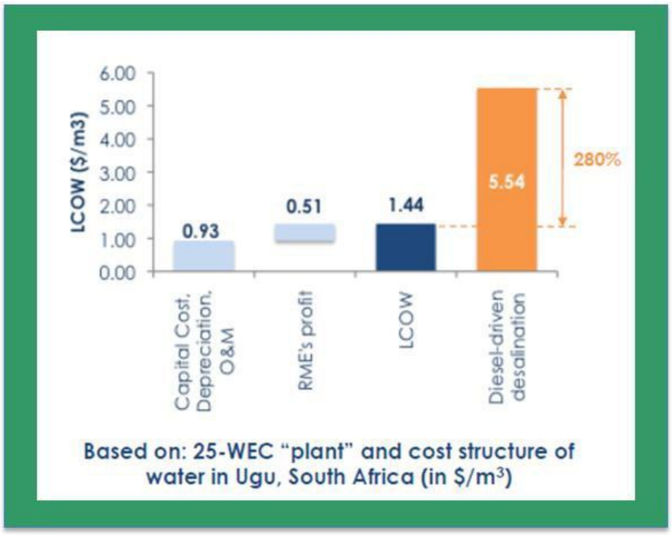


Figure 3. LCOW summary chart.

This compares very favorably to a diesel plant operating at $5.54/m^3.

2.2. Task 2: Establish Performance Requirements for Commercial-Scale Subsystem(s):

Having established performance requirements for the fully-integrated system in Task 1, the focus of Task 2 will be to determine the performance requirements for the Subsystem.

To begin, we examined the wave energy environment in South Africa and found South Africa has a significant offshore wave power resource. Wave data recorded at wave-measuring stations operated by the Council for Scientific and Industrial Research (CSIR) on behalf of the National Ports Authority South-west coastal zone has the greatest wave energy resource, with a mean annual average of approximately 40kW/m. The rest of the South African coast is exposed to average wave power that is between approximately 18 and 23 kW/m.

The figure below is measured data gathered in accordance with *E2I EPRI Specification: Guidelines for Preliminary Estimation of Power Production by Offshore Wave Energy Conversion Devices*" off the eastern coast of South Africa. The scatter diagram is a frequency of occurrence of wave states for periods measured in seconds at corresponding wave heights, measured in meters. The highlighted green box in Table 1 summarizes the predominant occurrence that RME will use in sizing the SurgeWEC capturing a totally frequency of occurrence of 88.5% of the available weave energy.

Table 1. CSIR Data for South Africa: Wave Power Density per Sea State

HMo (M)	Period (s)															
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10	10 -	12 -	14 -	16 -	18 -	20 -	22 -	24 -	26 -	28 -	30 -	Total
0.0 -																	
0.5 -			0.11	0.49	0.81	1.90	0.62	0.17	0.01	0.01							4.11
1.0 -		0.02	2.20	6.38	6.86	13.04	5.39	2.57	0.26	0.07	0.04	0.01					36.82
1.5 -			3.10	8.52	6.07	11.15	5.02	2.76	0.34	0.08	0.02						37.05
2.0 -			0.73	4.84	2.01	4.60	1.98	1.25	0.13	0.04	0.01						15.59
2.5 -			0.05	1.24	0.60	1.57	0.70	0.52	0.08	0.04							4.79
3.0 -				0.09	0.09	0.49	0.27	0.20	0.05								1.19
3.5 -				0.01	0.03	0.18	0.05	0.04	0.01								0.31
4.0 -						0.07	0.01	0.01									0.09
4.5 -						0.03											0.03
5.0 -						0.02											0.02
5.5 -																	
Total	0.00	0.02	6.18	21.													

From this data, we determined a wave energy matrix, in kW/m as shown in Figure 4 and the design point for the SurgeWEC:

- Paddle Design Conditions:
- Average Period: 11 s
- Wave Height: 1.75 m
- Annual Wave Power = 14.6 kW/m

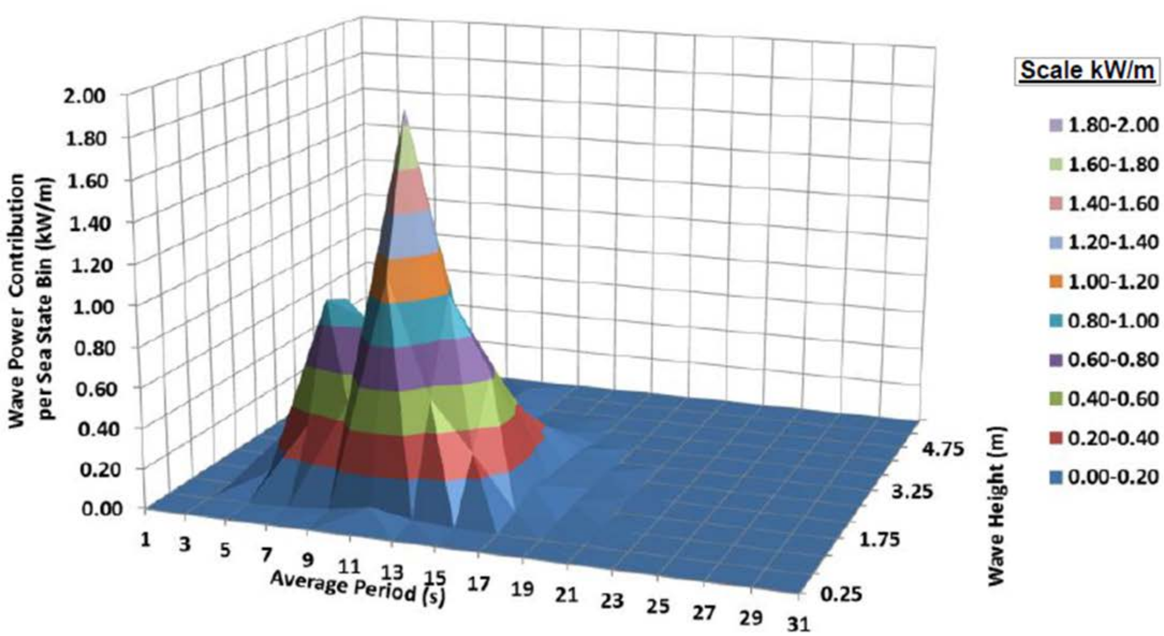


Figure 4. Wave energy matrix.

2.2.1. Overall System Architecture and Operating Parameters

Overall system architecture and operating parameters are shown in Figure 5.

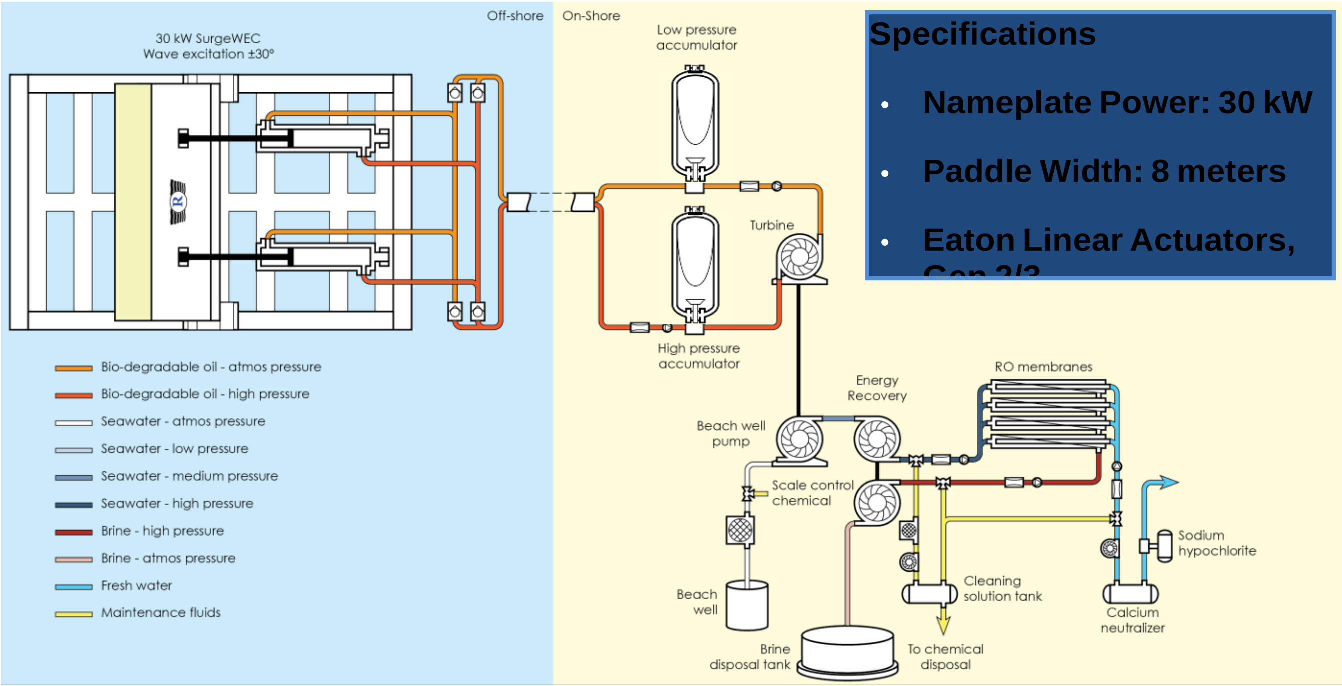


Figure 5. Overall operating parameters.

Parameters include:

- SWRO Desalination Plant: 750 kW producing 2000 m3/day of fresh water
- Power per SurgeWEC: 30kW nameplate rating
- SurgeWECs per plant: 25
- Hydraulic Architecture
  - Closed-loop hydraulic with SWRO on-shore
    - Average pressure and flow requirement: 2000 psi and 50 gpm
    - PTO: dual linear hydraulic cylinders or rotary actuators
    - High pressure fluid drives turbine or hydraulic motor for RO high pressure pump
    - Working fluid: UCON™ Trident™ AW Hydraulic Fluids made by DOW
  - SWRO Open Loop salt water system
    - Open loop system pulling salt water from beach well thru SWRO back to ocean
    - System power using closed loop bio-degradable oil from SurgeWEC thru turbine/hydraulic motor drives high pressure salt water pump
    - Standard SWRO system with turbo-boost energy recovery pump
    - Brine diluted with beach well water prior to return to ocean

- Auxiliary PTO driven induction generator to power control system / valves

2.2.2. Power Take-off Approach

Currently, RME is investigating two primary options for converting the periodic motion of the SurgeWEC into hydraulic power: linear hydraulic cylinders (LHC) and rotary pumps. Detail efforts are underway with the lead vendor for each solution. Figure 6, Figure 7, and Figure 8 are concepts for implementation as well as preliminary sizing estimates for the rotary pump; the LHC solution is in process.

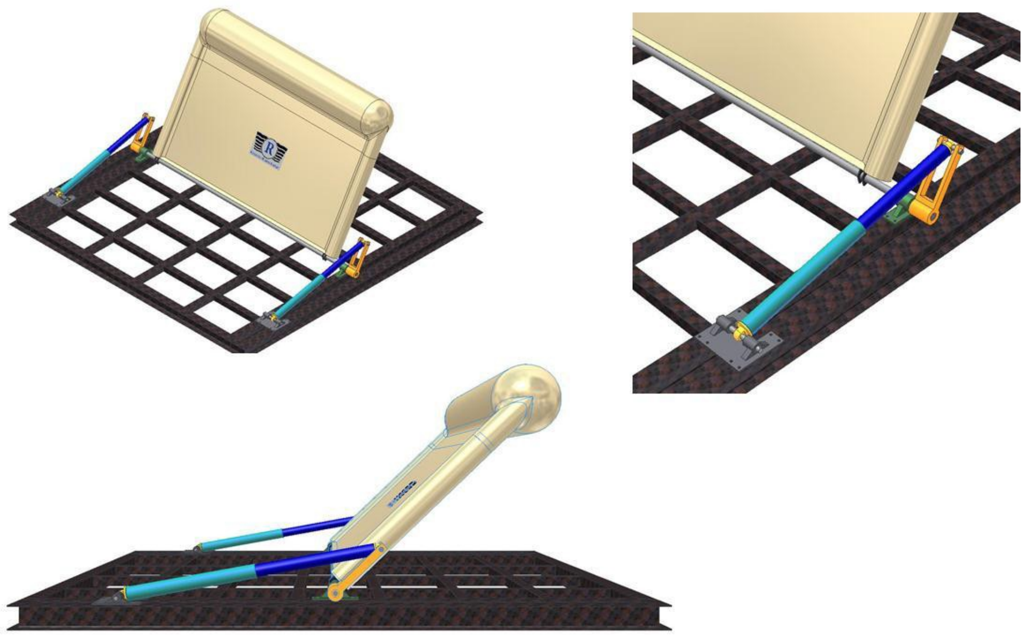


Figure 6. Linear hydraulic cylinder PTO drive concept.

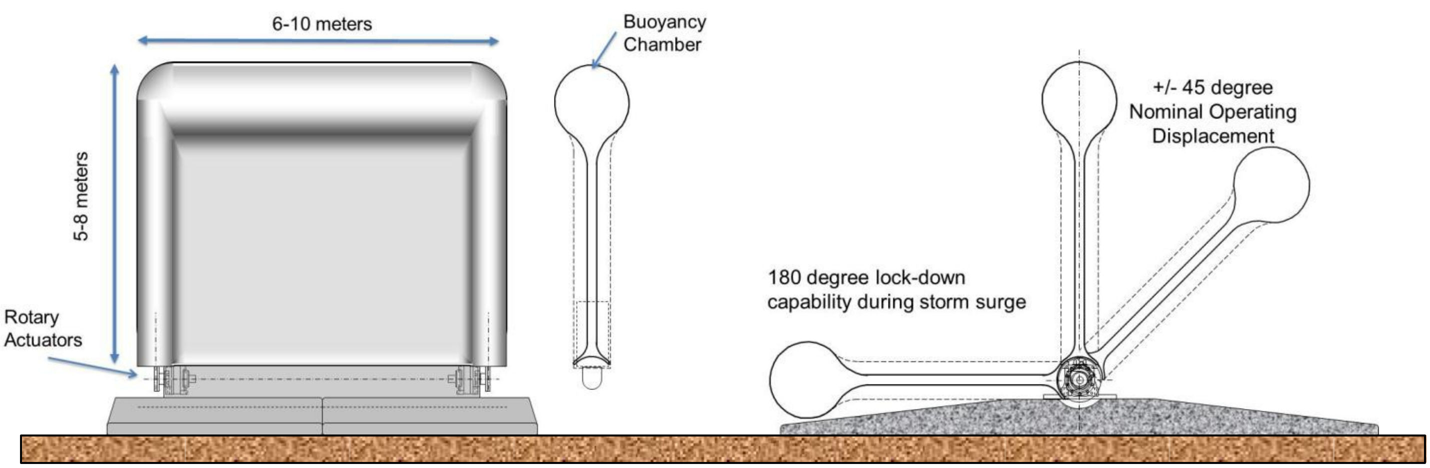


Figure 7. Rotary actuator concept.

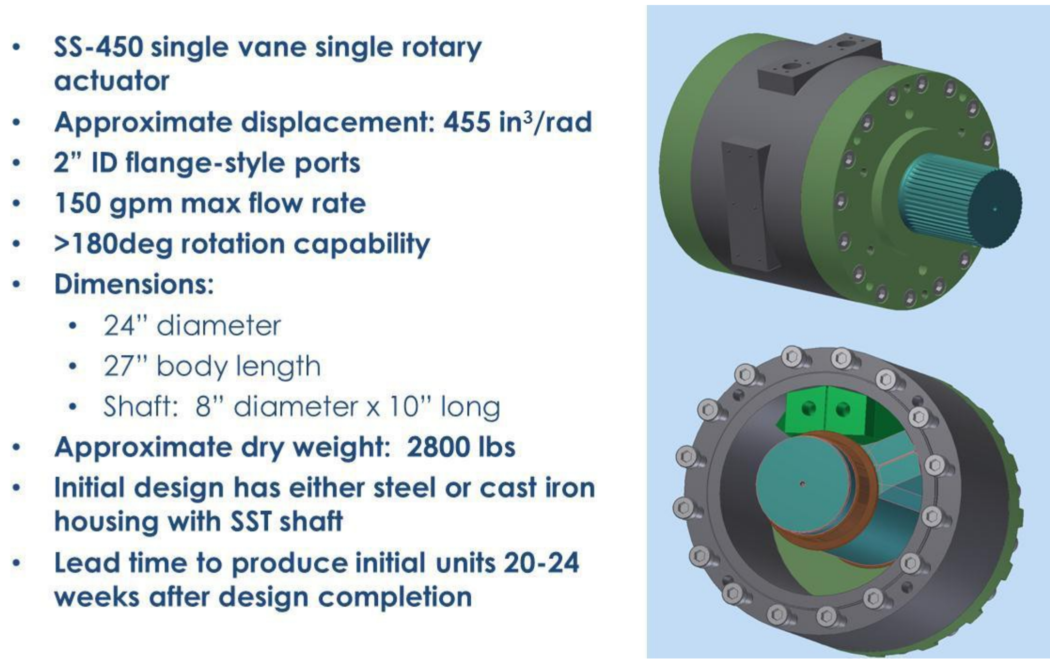


Figure 8. Custom rotary pump.

2.2.3. Hydraulic Accumulators

Hydraulic accumulators are energy storage devices that smooth the pulsation of pumps. Accumulators help maintain a constant fluid pressure during temporary changes of demand. Pulsation dampeners are attached placed as close as possible to the pump output to moderate the pump's pressure and volume fluctuations.

Reciprocating piston pumps (such as LHC or rotary actuators) achieve high pressures, however tend to produce the strongest output pulsations. The dampener inlet should be no smaller than the pump outlet pipe diameter or they will restrict the flow into and out of the dampener. The dampener should be pre-charged with nitrogen to 70 to 80% of the system mean operating pressure.

Preliminary sizing analysis indicates that to achieve the desired low-pressure ripple content, a high pressure accumulator or approximately 25 gallons is required (Figure 9). The accumulators are off-the-shelf items and are readily available.

2.2.4. Hydraulic Motor

RME plans to use a variable displacement positive displacement hydraulic motor to convert the closed loop hydraulic fluid from the SurgeWEC into shaft power to drive the high-pressure pump of the SWRO desalination plant. Current sizing analysis indicates at flow of 50 gpm at an operating pressure of 2000 psi will be sufficient for a single SurgeWEC paddle. Currently, we are considering using a Rexroth solution, although we are also looking at options from Eaton Corporation. The Rexroth solution is shown in Figure 10 for reference:

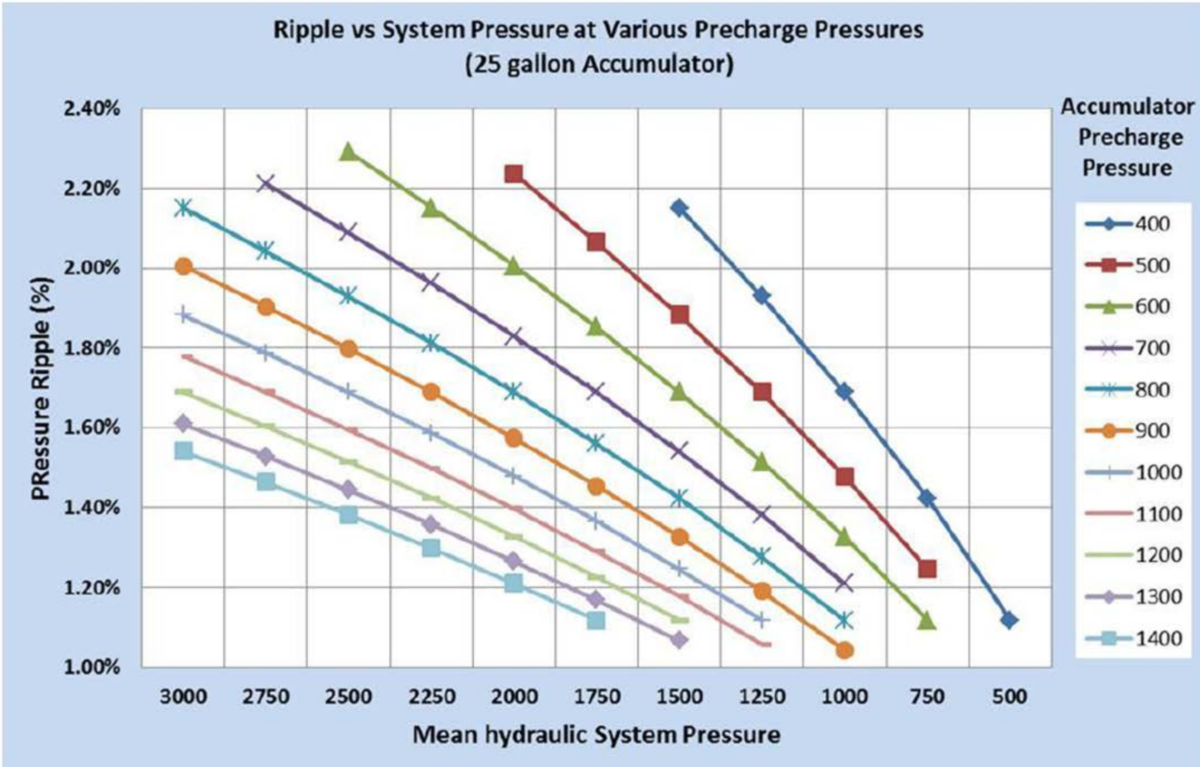
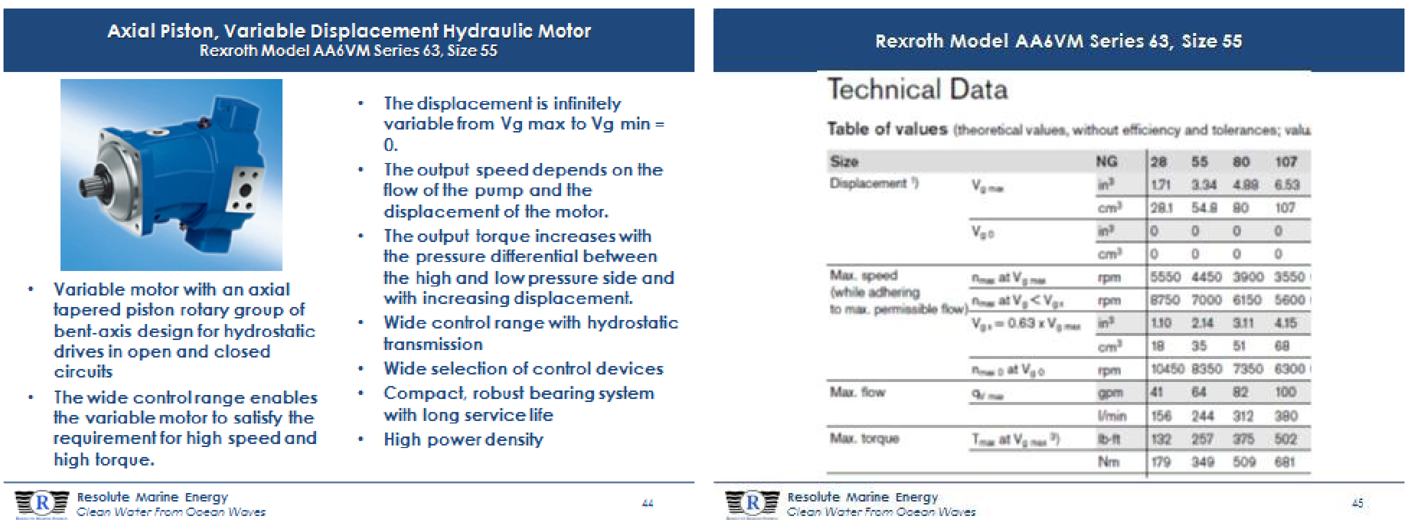


Figure 9. Ripple vs. system pressure at various precharge pressures



Size		NG	28	55	80	107
Displacement [1]	$V_{g\,max}$	in³	1.71	3.34	4.88	6.53
		cm³	28.1	54.8	80	107
	$V_{g\,0}$	in³	0	0	0	0
		cm³	0	0	0	0
Max. speed (while adhering to max. permissible flow)	n_{max} at $V_{g\,max}$	rpm	5550	4450	3900	3550
	n_{max} at $V_g < V_{g\,x}$	rpm	8750	7000	6150	5600
	$V_{g\,x} = 0.63 \times V_{g\,max}$	in³	1.10	2.14	3.11	4.15
		cm³	18	35	51	68
	$n_{max\,0}$ at $V_{g\,0}$	rpm	10450	8350	7350	6300
Max. flow	$q_{V\,max}$	gpm	41	64	82	100
		l/min	156	244	312	380
Max. torque	T_{max} at $V_{g\,max}$ [3]	lb-ft	132	257	375	502
		Nm	179	349	509	681

Figure 10. Rexroth solution.

2.2.5. Sea Water Reverse Osmosis Plant

For the first installation in South Africa, RME will partner with a SWRO supplier to provide a turnkey solution. Currently, RME is in discussion with Danfoss – a leading supplier of SWRO systems. Given the design output of 80 m^3 per day for the single

SurgeWEC system, we anticipate interfacing to either the Model 85 or 105 system. RME will work with the SWRO supplier to integrate the Wave2O control system and direct shaft couple hydraulic motor to the SWRO high pressure sea water pump. Using the Danfoss communication package, the Ethernet communication bus can seamlessly be integrated with RME controller allowing real-time control, as well as process instrumentation, system performance, and error detection and remediation monitoring (Table 2).

Table 2. System Specifications

SYSTEM SPECIFICATIONS

Model	No. of Vessels	Membrane Configuration	Production / Hour	Production / 24 Hrs.	Weight - lbs / kg
45m^3	1	Double	498 gal / 1,887 lit	11,961 gal / 45,280 lit	3,700 lbs / 1,678 kg
85m^3	2	Double	938 gal / 3,549 lit	22,502 gal / 85,180 lit	4,000 lbs / 1,814 kg
105m^3	3	Double	1,169 gal / 4,425 lit	28,056 gal / 106,210 lit	4,300 lbs / 1,950 kg
145m^3	4	Double	1,627 gal / 6,160 lit	39,051 gal / 147,830 lit	4,800 lbs / 2,177 kg
175m^3	6	Double	1,947 gal / 7,371 lit	46,734 gal / 176,910 lit	5,400 lbs / 2,449 kg
175m^3	4	Triple	1,947 gal / 7,371 lit	46,734 gal / 176,910 lit	5,400 lbs / 2,449 kg
200m^3	6	Triple	2,158 gal / 8,313 lit	51,791 gal / 199,500 lit	6,300 lbs / 2,857 kg

2.3. Task 3: Establish Parameters for Testing a Bench-Scale Subsystem

RME plans to conduct an ocean system test in November 2012 of a sub-scale 5kW SurgeWEC system using a 5 m paddle powering an induction generator using the pressure regulation and flow subsystem developed under this DOI program. The DOI project will be the scaled to the 5 kW level and bench top tested lab tested in the lab in the October timeframe and then will also be used in the ocean test in November (Figure 11 and Figure 12)

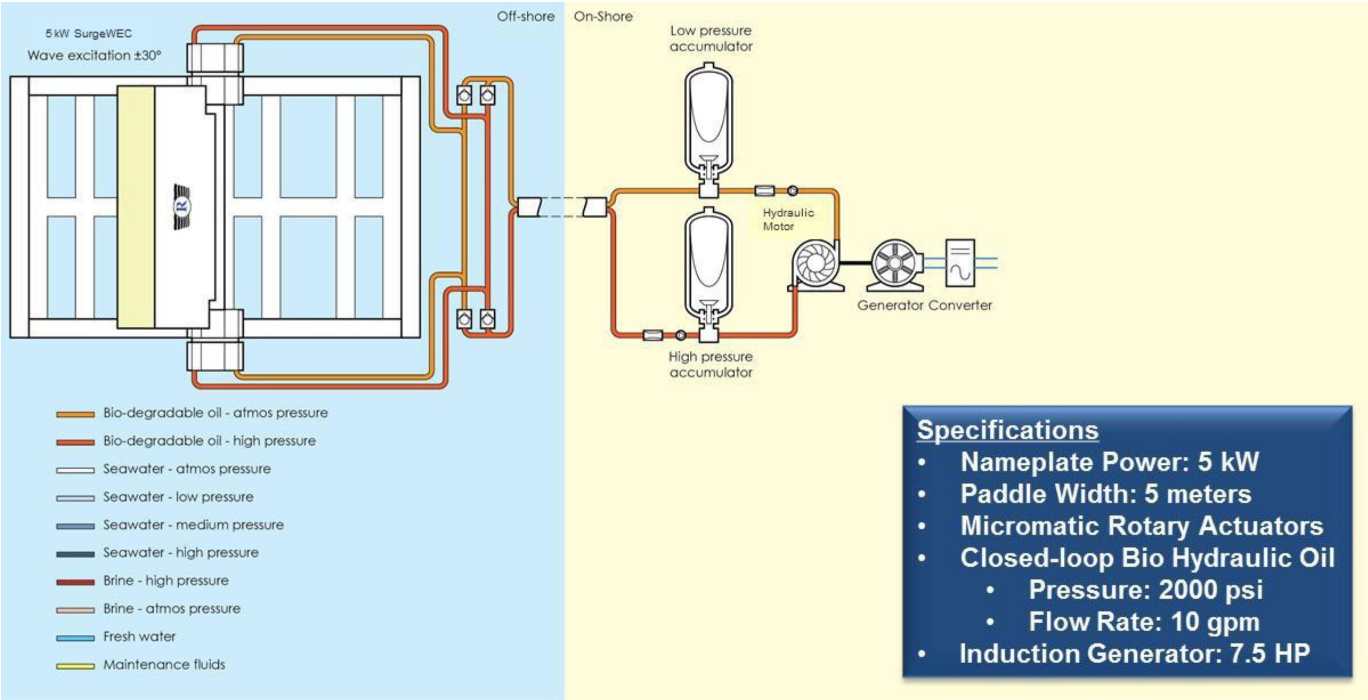


Figure 11. Schematic diagram of the ocean system.

Figure 12. Photo of ocean system.

2.3.1. Hydraulic System Schematic

A schematic has been derived from the architecture shown above for the benchtop system with the slight modification of modeling the SWRO plant as a variably configurable hydraulic load bank (Figure 13). This will allow us to develop and test control algorithms as we anticipate needing for the desalination plant implementation. The control system will be easily reconfigured for the ocean testing to manage the induction generator output.

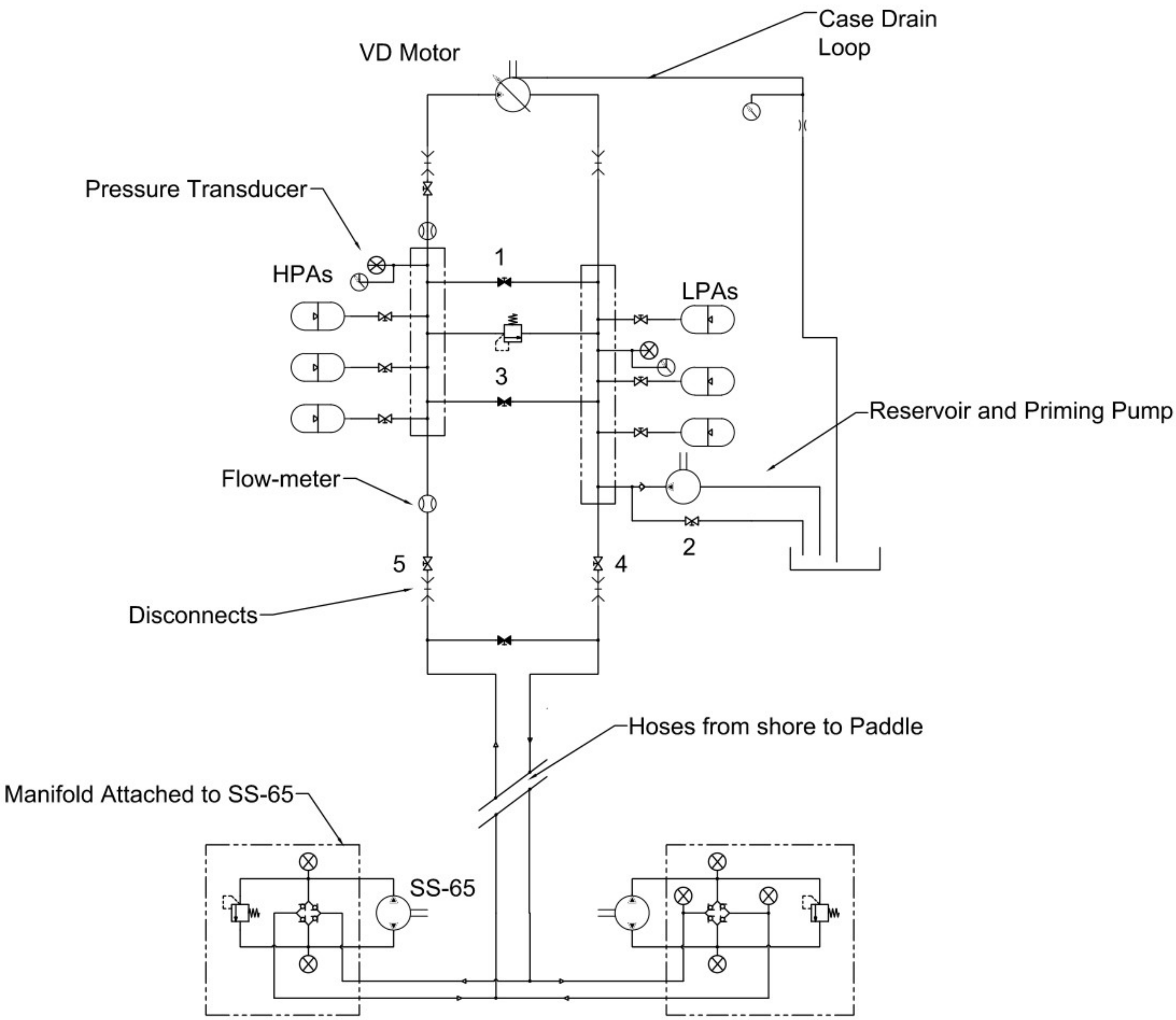


Figure 13. Hydraulic system schematic.

As a next step in the sizing exercise, we developed an overall Simulink Model using MathCAD Simulink computer modeling tool (Figure 14) and a Variable Displacement Motor Model (Figure 15).

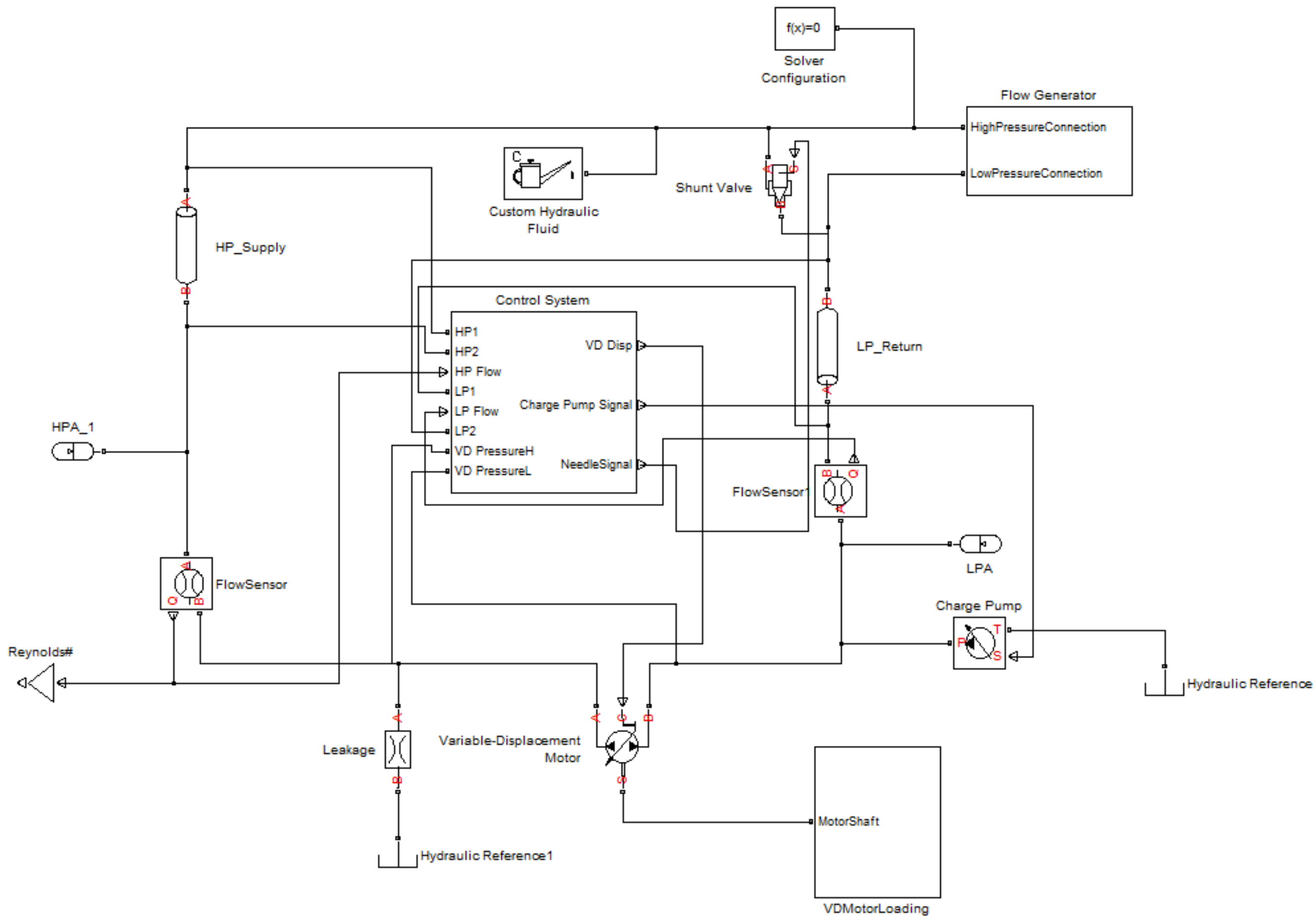


Figure 14 Overall Simulink Model.

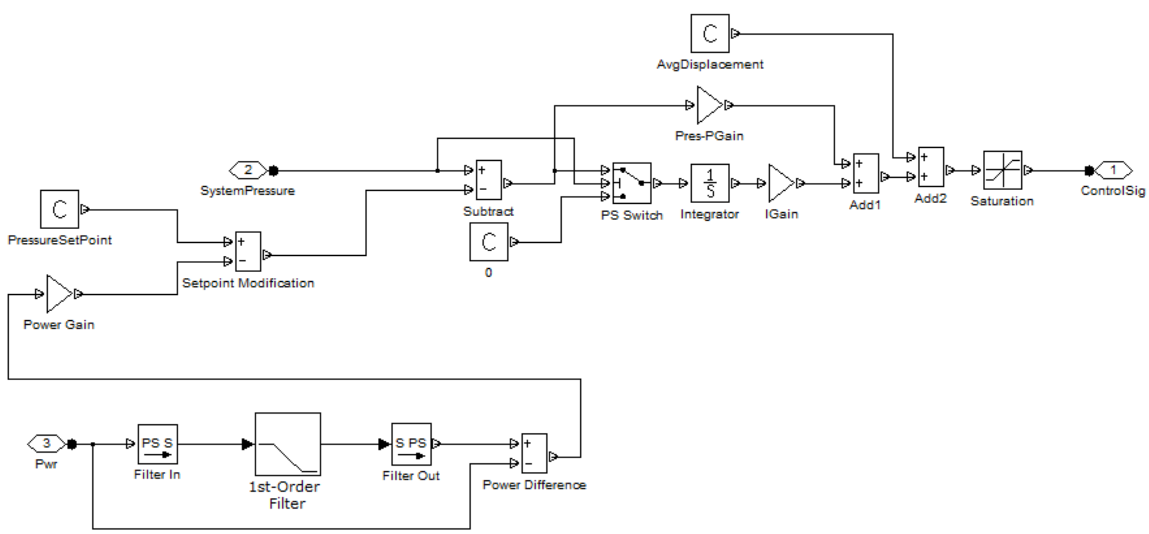


Figure 15 Variable Displacement Motor Model.

2.3.2. Model Input Parameters

Model input parameters are shown in Figure 16.

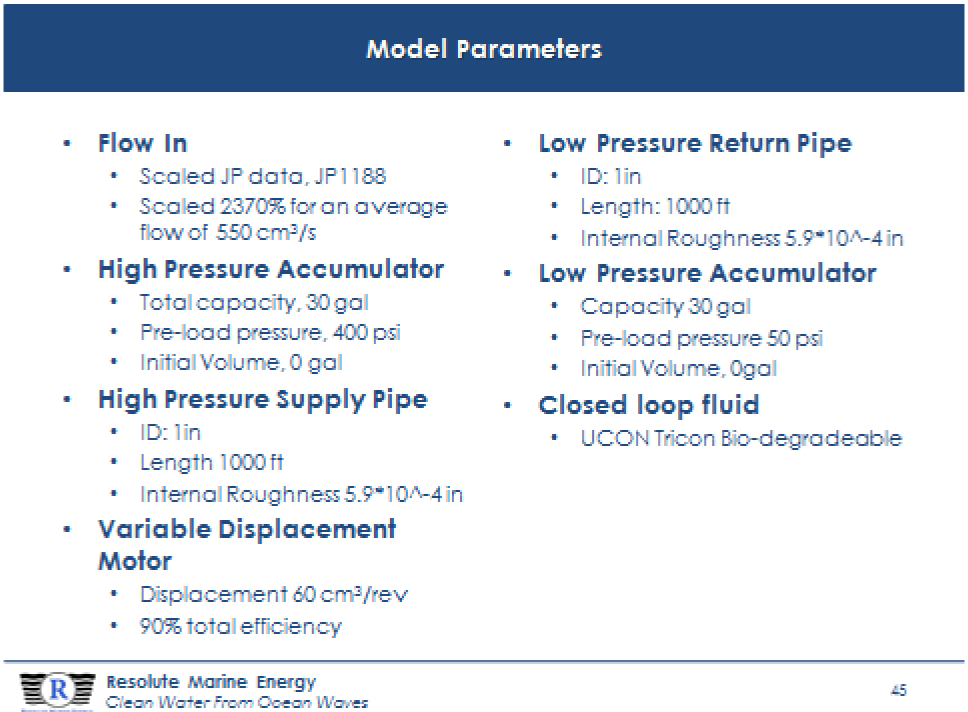


Figure 16. Model input parameters.

2.3.3. Model Input

As an input to the model to simulate the incident wave energy, RME scaled data taken from ocean testing we had conducted in North Carolina on a 2.5 m SurgWEC paddle (Figure 17). Those results were scaled to approximate the anticipated input power for our fall ocean test. Results are shown in Figure 18.

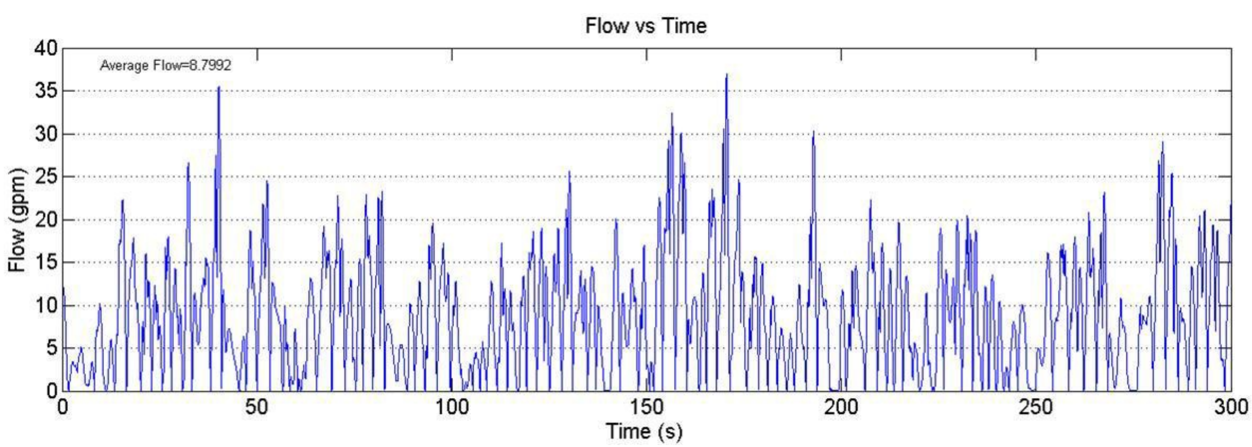
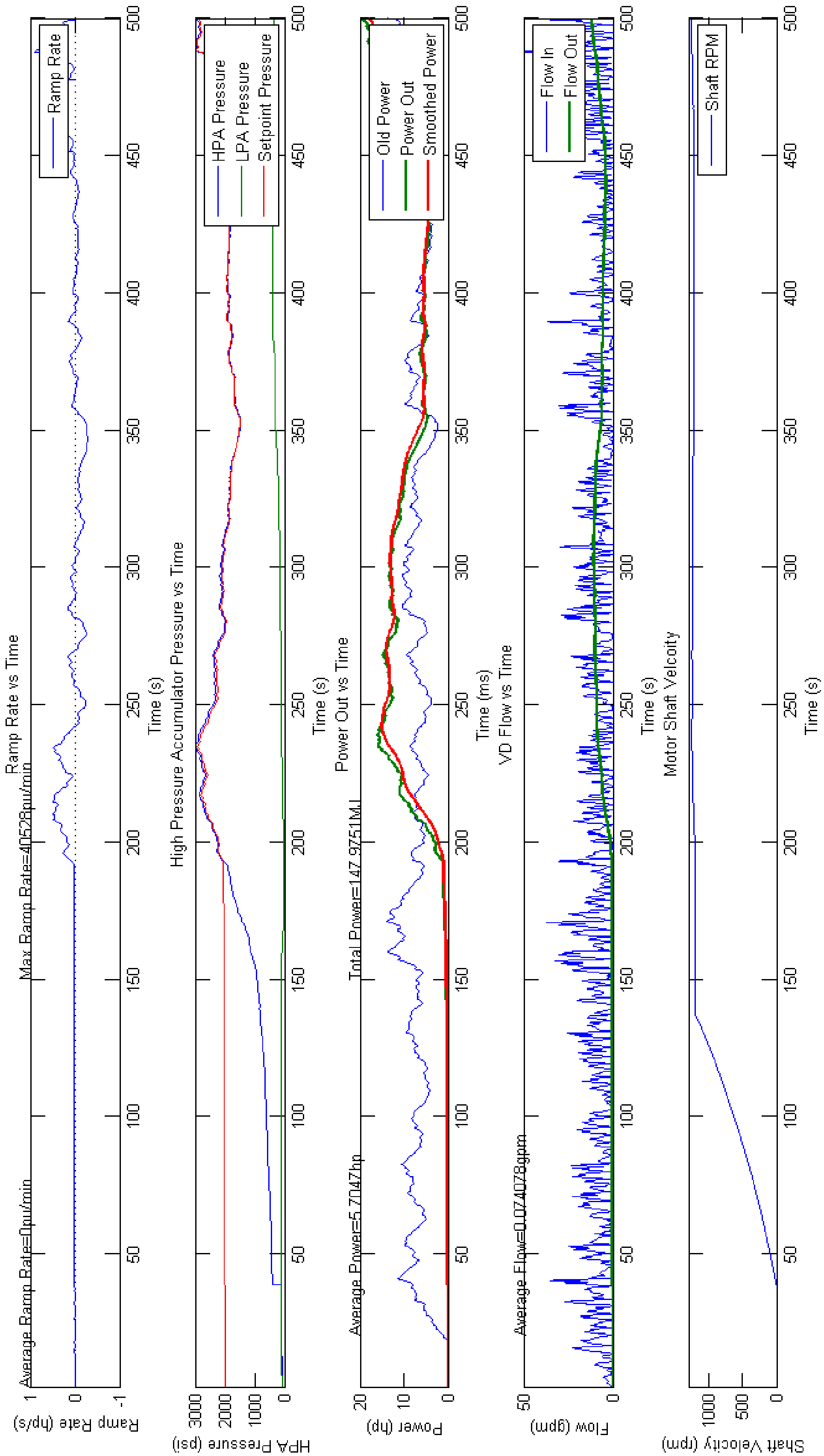


Figure 17. Scaled data flow.



Ramp Rate vs Time
Average Ramp Rate=0pu/min
Max Ramp Rate=40528pu/min
Ramp Rate
Ramp Rate (hp/s)
Time (s)
High Pressure Accumulator Pressure vs Time
HPA Pressure
LPA Pressure
Setpoint Pressure
HPA Pressure (psi)
Time (s)
Power Out vs Time
Average Power=5.7047hp
Total Power=147.9751MJ
Old Power
Power Out
Smoothed Power
Power (hp)
Time (s)
VD Flow vs Time
Average Flow=0.074078gpm
Flow In
Flow Out
Flow (gpm)
Time (ms)
Motor Shaft Velcoity
Shaft RPM
Shaft Velocity (rpm)
Time (s)

Figure 18. Results.

2.4. Task 4: Build bench-scale apparatus that simulates SurgeWEC

2.4.1. PTO Test Apparatus – Development Center

RME plans to use a hydraulic actuator connected to a Micromatic HS-10 rotary actuator driven as a pump. The hydraulic apparatus has been procured for test of another RME WEC device (financed by a DOE SBIR grant) and it will be adapted for testing the DIO PTO. The test apparatus assembled in our laboratory is depicted in Figure 19. The hydraulic apparatus has a micro-controller interface that allows various input profiles simulating incident wave energy levels, frequencies and overall profiles to drive the cylinder. Additionally, RME has a number of digitized actual real wave profiles from previous ocean tests that will be used in the DOI testing as well.

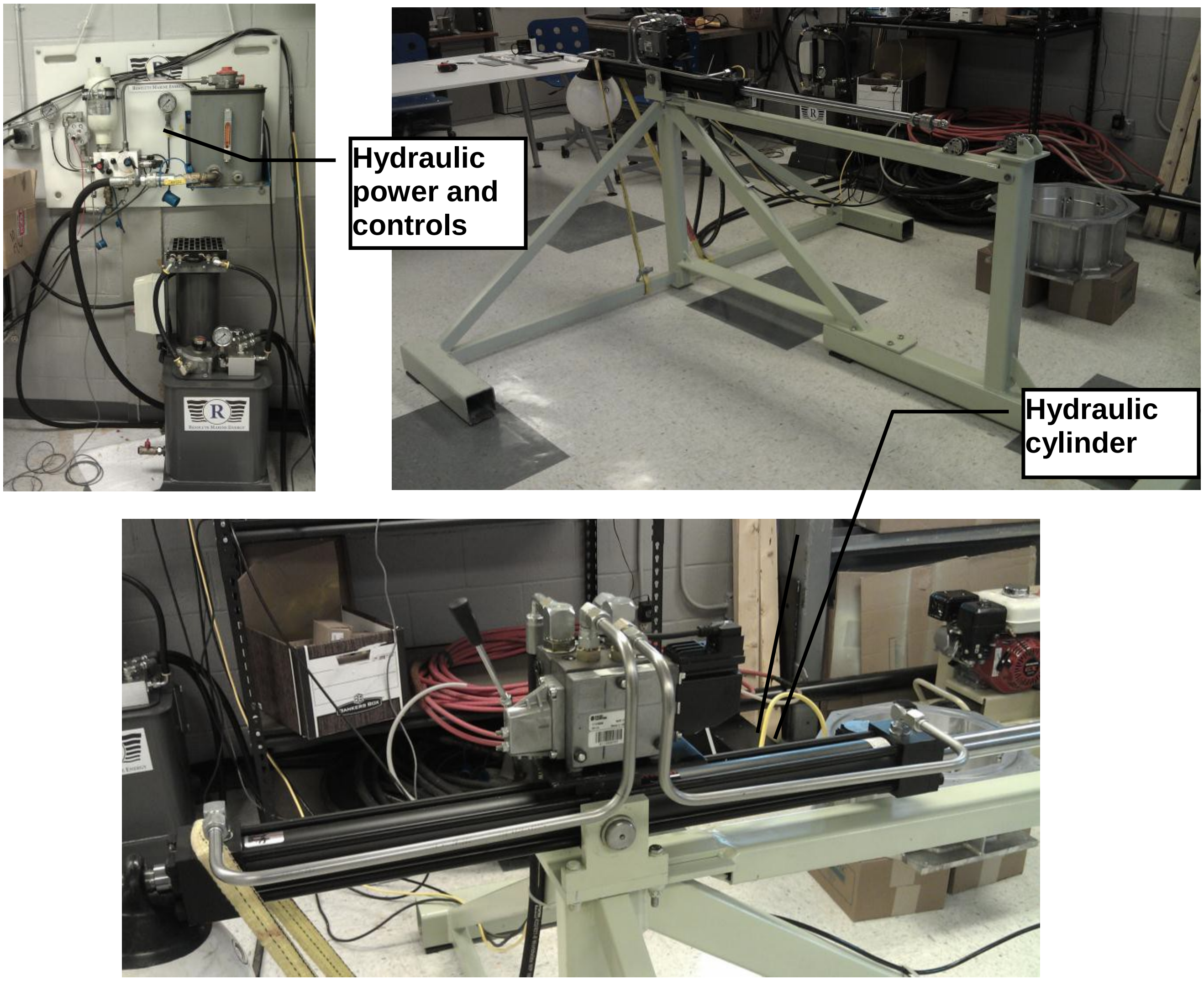


Figure 19. Test apparatus.

The hydraulic test rig was modified to add a support structure for the HS-10 and a pivot arm that converts the linear hydraulic cylinder motion in to a rotary motion thereby driving the actuator as a pump (Figure 20).

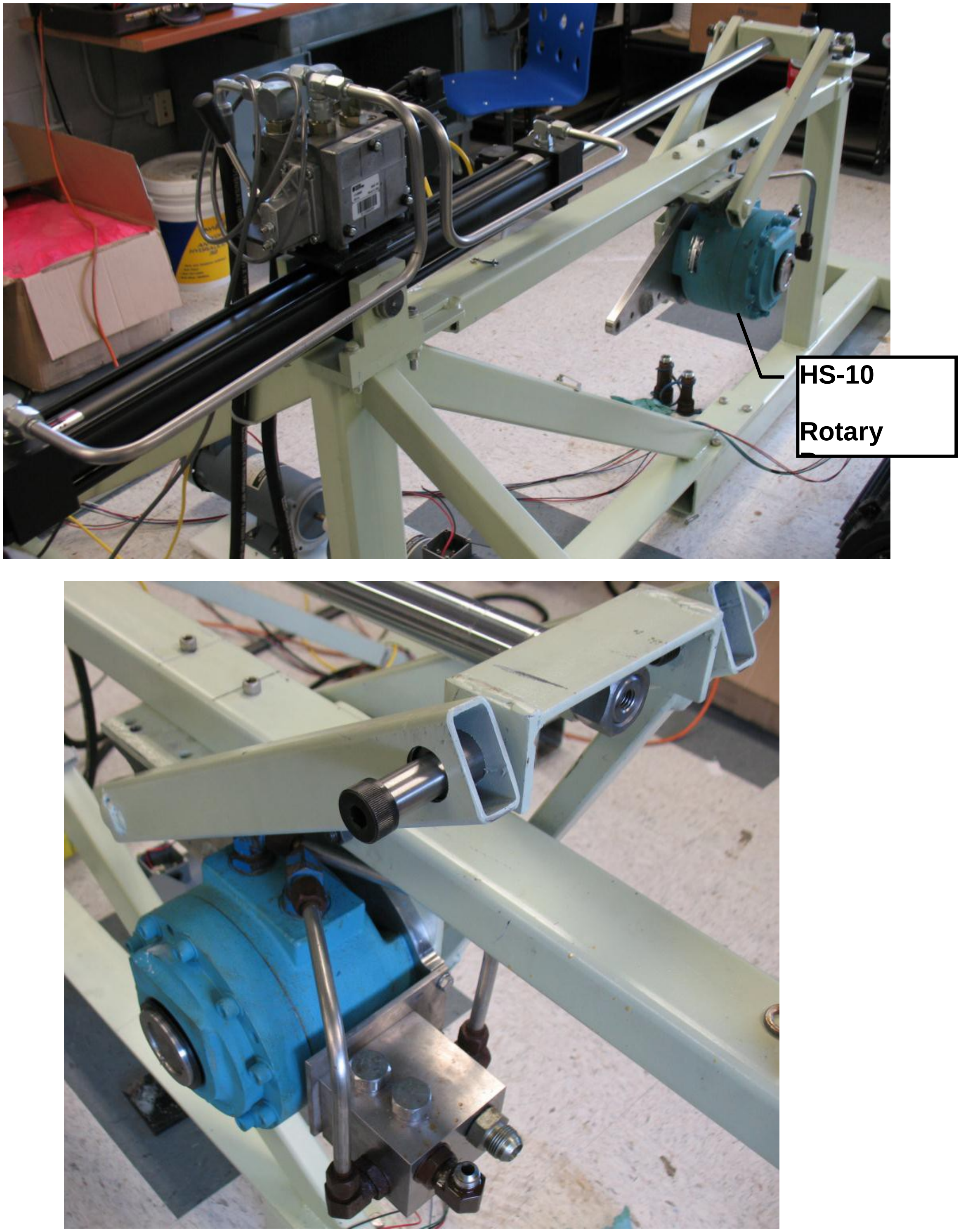


Figure 20. Hydraulic test rig.

2.4.2. Generator and Hydraulic Motor

The pressurized fluid from the HS-10 pump flows through the hydraulic motor and drives the induction generator (Figure 21).

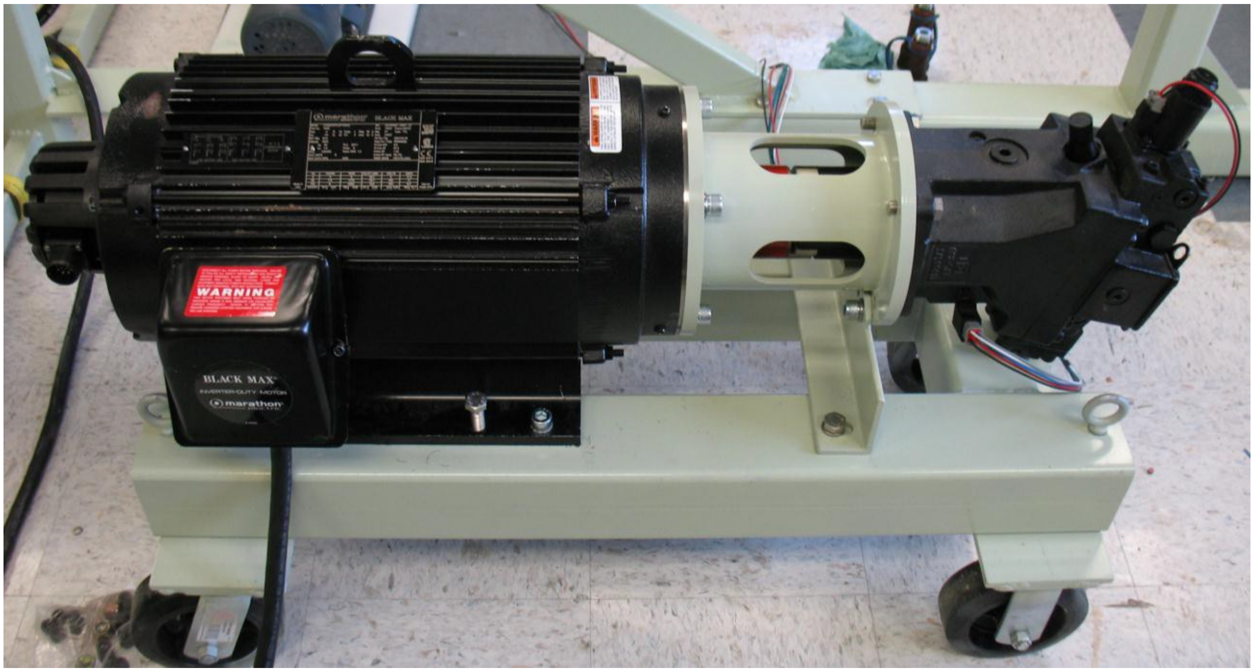


Figure 21. Induction generator.

2.4.3. Generator and Load Bank Controller

The electrical control power from the generator is managed thru the Generator and Load Bank Controller (Figure 22). The load bank is shown in

Figure 22.Generator and load bank controller.

2.4.4. System Controller

The overall control of the complete system is managed by the system controller shown in Figure 23. The controller controls the input ocean wave model, which in turn sends a control signal to drive the hydraulic ram which in turn pumps fluid thru the hydraulic motor. Flow is smoothed using the system controller algorithms and augmented by the hydraulic accumulators.

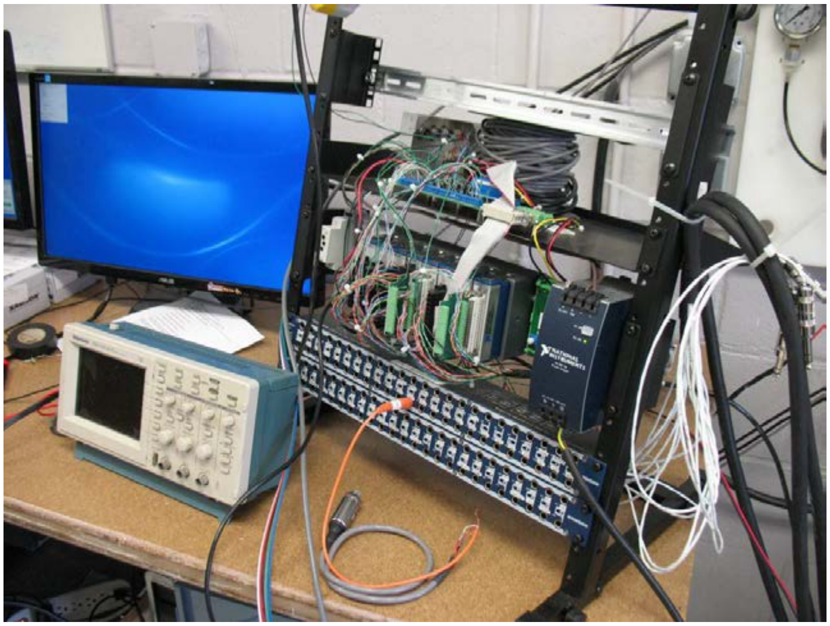


Figure 23. System controller.

2.4.5. Hydraulic Accumulators/Pulsation Dampeners

Hydraulic accumulators/pulsation dampeners are shown in Figure 24.

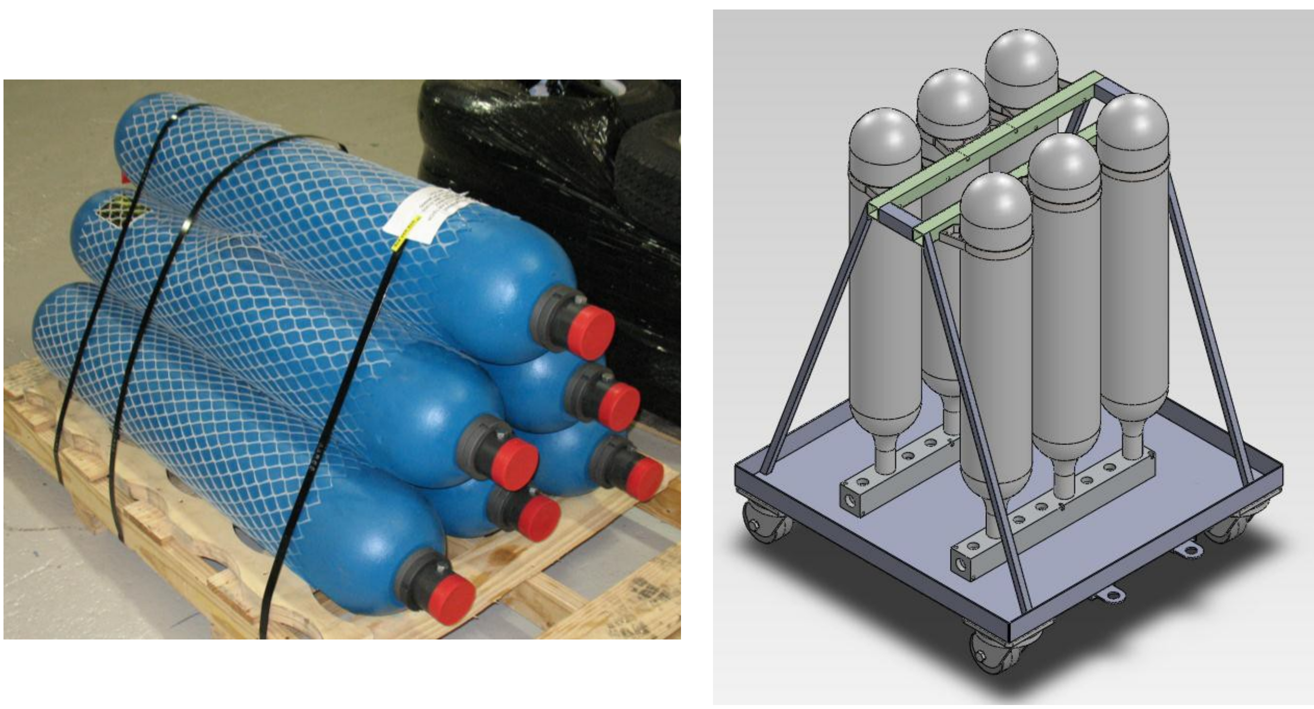


Figure 24. Hydraulic accumulators/pulsation dampeners.

2.4.6. Load Bank

To dissipate the power generated by the generator, a load bank comprised of oil filled radiators is used (Figure 25).

Figure 25. Load bank.

The PTO Subsystem was fully assembled at Newburyport Clean Technology Center and operational tested to make sure all systems functioned as designed, the system was leak tight, and that the control system met all operational, control, and safety requirements. Following this check-out testing, the system as disassembled into its major subsystems and shipped to the US Army Corp of Engineers Field Research Facility in Duck North Carolina for field testing. The installation and testing results will be discussed in the following section.

2.5. Task 5: Test the Bench-Scale Subsystem – US Army Corp of Engineers Field Research Facility

Upon arrival of the equipment at Duck, North Carolina from Newburyport, Massachusetts, the team began assembly of the subsystems as shown in the following set of images. Figure 26 shows the PTO subassembly which is comprised of a MicroMatic SS-65 Rotary Actuator connected to a flow rectification manifold. The flow rectification manifold is a set of check valves, pressure sensors, and pressure-by-

pass relief valves that converts the bi-directional oscillating flow generated by the SurgeWECs as it captures the bi-directional
wave energy out of the SS-65s into a unidirectional time varying pressure/flow which is pumped to the Pressure / Flow Regulation subsystem shown in Figure 27.

The Pressure/Flow Regulation Subsystem is comprised of 3 high pressure accumulators (HPA) and 3 low pressure accumulators (LPA). The pre-charge pressure in the accumulators can be adjusted however during the test series; we found that an ideal setting of 400 psi in the HPA and 100 psi in the LPA provide acceptable results. Additionally in Figure 27, one can observe the hydraulic motor connected to the induction generator (middle set of equipment) and the load bank resistors (right set of equipment. The hydraulic hoses seen entering the Pressure / Flow Regulation Subsystem are connected to the PTO assemblies attached to the SurgeWEC (submerged in the ocean next to the Duck Pier in 5 meters of water.
Figure 28 shows the fully assembled control system and data acquisition subsystem. Data samples were taken at 100 Hz. The controller provided real-time control to the pressure/flow regulation subsystem as well as control of the hydraulic motor and induction generator.

Figure 29 show in the fully assembled SurgeWEC ready for deployment. Figure 5-5 shows the paddle being deployed. RME has developed at methodology by which we can assemble and launch the SurgeWEC directly from the beach – hence we call this process a Beach Launch. This approach is very low costs and does not require the use of expensive surface vessels, spud barges, or cranes.

Finally Figure 30 and Figure 31 are shown two sample output runs. The pressure and flow regulation system worked extremely well as can be seen from the plots. The goal was to achieve less than a 10% ripple in both the flow and pressure and as can be seen from the plots, RME was able to achieve these objectives. The pressure range tested included the ~500 psi shown in Figure 32 as well as pressures up to 2000 psi with similar performance results.

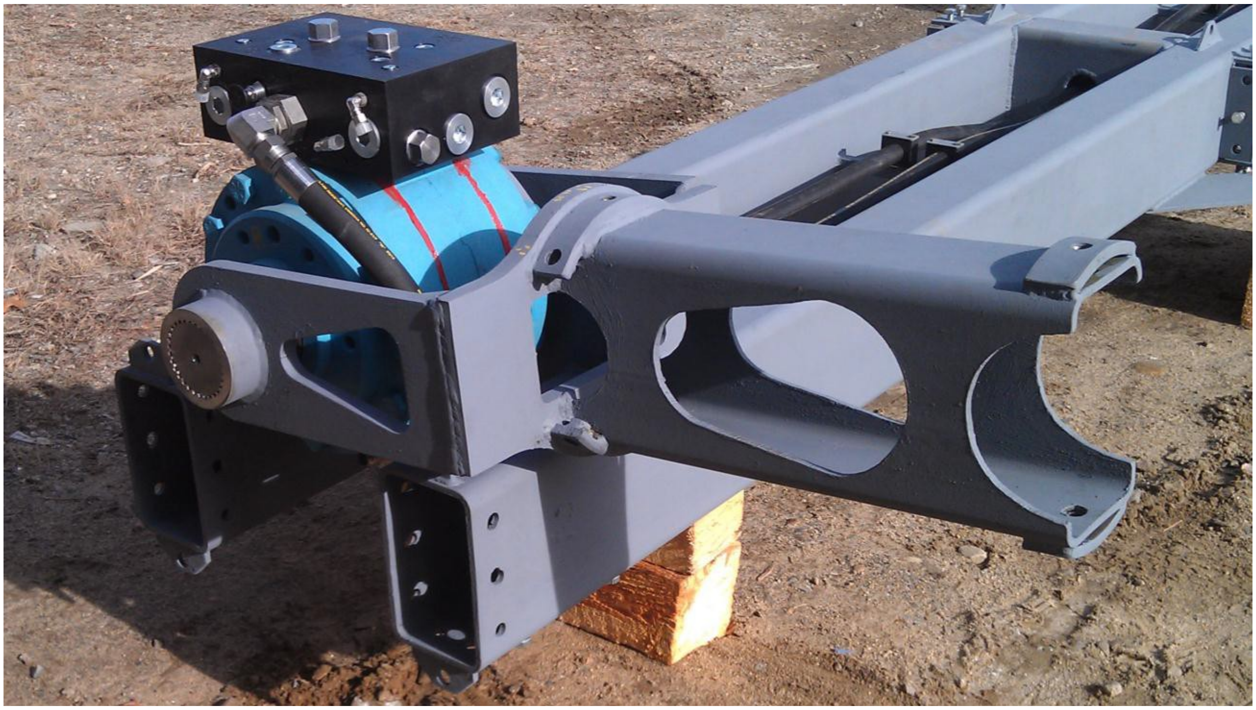


Figure 26. PTO subassembly.

Figure 27. Pressure/Flow Regulation, Generator, and Load Bank Subassemblies

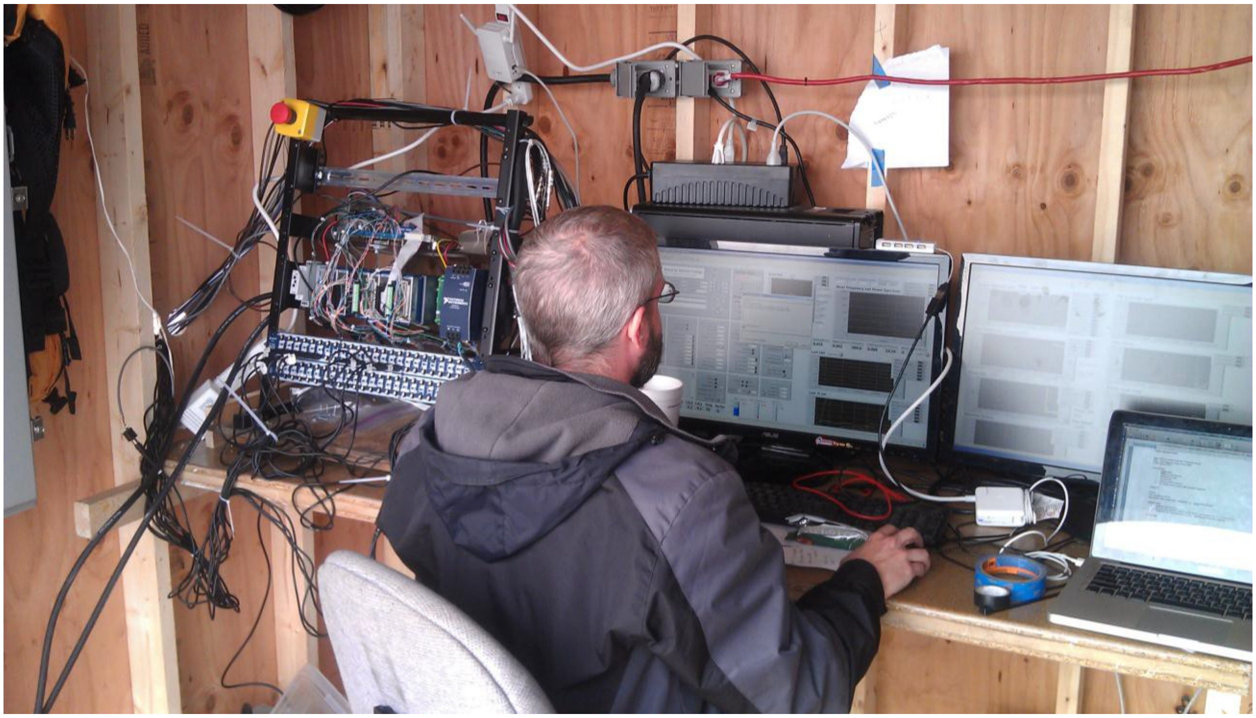


Figure 28. Control center.

Figure 29. Fully Assembled SurgeWEC and PTO Subassembly

Figure 30. Beach Launch and Deployment of SurgeWEC.

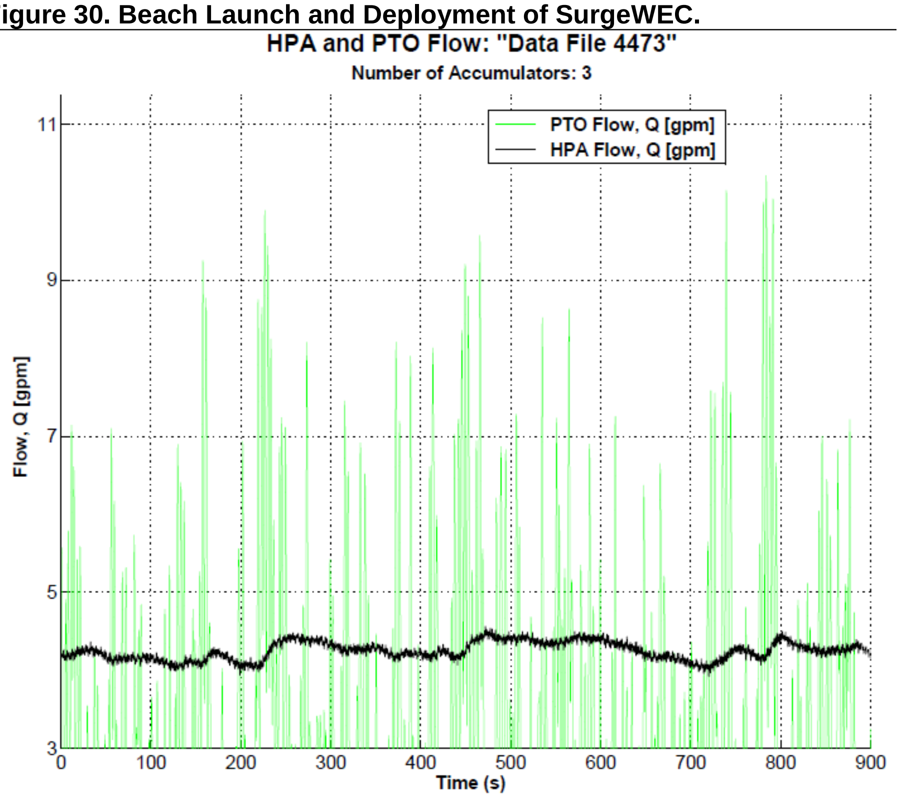


Figure 31. Flow vs time showing flow out of SurgeWEC PTO and smoothed flow out of Pressure/Flow Regulation Subsystem

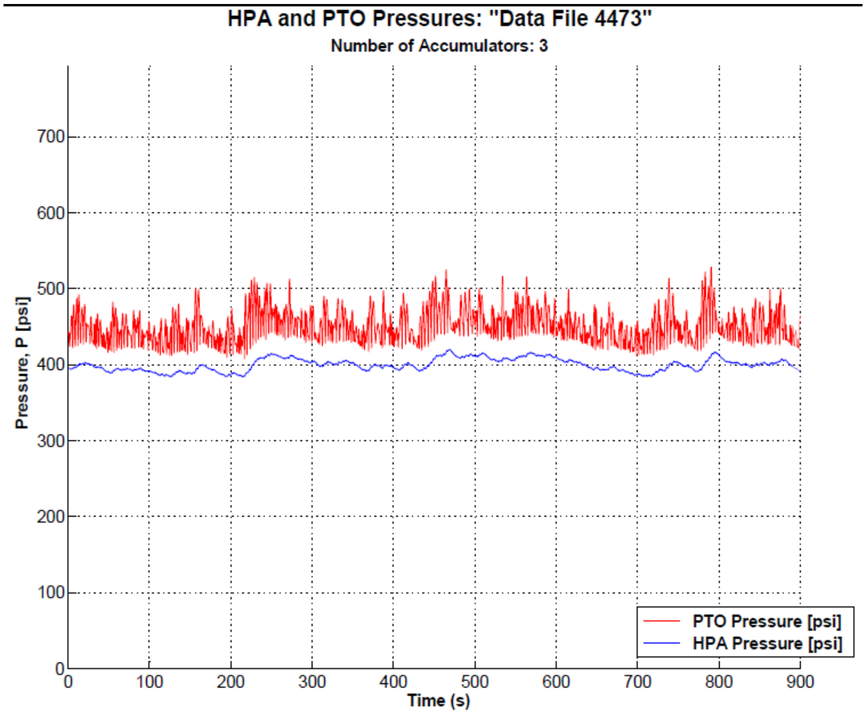


Figure 32. Pressure vs time showing pressure out of SurgeWEC and smoothed pressure out of Pressure Regulation Subsystem

2.6. Task 6: Perform Manufacturing Cost Analysis of the Subsystem

RME completed a thorough analysis of all the costs that should be factored to calculate the Levelized Cost of Water (LCOW) of the integrated wave-energy driven desalination system described in task 2 using a methodology recommended by NREL ("A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies", March 1995).

The LCOW is that cost that, if assigned to every unit of water produced (or saved) by the system over the analysis period, will equal the Total Life-Cycle Cost ("TLCC") when discounted back to the base year. The TLCC consists in the costs incurred (discounted to a base year) through the ownership of an asset over the asset's life span.

$$LCOW = \frac{TLCC}{\sum_{i=0}^{N} \frac{Q_i}{(1+d)^i}}$$

$$TLCC = \sum_{i=0}^{N} \frac{C_i}{(1+d)^i}$$

Where:

LCOW=	Levelized Cost Of Water TTLC =	Total Life-Cycle Cost
Qn =	Water output or saved in year n	
Cn=	Cost in period n: investment costs include finance charges as appropriate; expected salvage value; nonfuel O&M and repair costs; replacement costs; and energy costs	
d =	Discount rate	
N =	Analysis period	

For the LCOW calculation the costs data were based on the following work stream carried on by RME over the duration of the project:

Wave Energy Converter (WEC) and pressure regulation system capital costs: based on the current Bill Of Material for the deployment of the full-scale (5-meter wide) WEC in Q4 2012
Desalination system capital costs: Based on industry data for different desalination subsystems at different production capacity.

Installation and civil engineering costs: based on our current installation and civil engineering budget for our first commercial pilot in South Africa estimated in partnership with the Council of Scientific and Industrial Research (CSIR) and with WSP a global civil engineering firm

Maintenance and operations costs based on industry standard.

We also assumed a learning curve for all of these cost items as a function of the number of plant installed and of the size of the plant enabling us to estimate how the LCOW will decrease as we have more plants installed. For example, we assume that the WEC manufacturing costs will decrease by 15% each time the capacity installed (above 1MW) double, a learning curve very similar to the one experienced in the wind industry. All these data are available upon request.
In term of sales assumption we assumed that RME would install:

1 plant in 2014
4 plants in 2015
8 plants in 2016

This represents a total of 13 cumulative plants installed by 2016, which is much lower than the current demand expressed by our pilot customer (between 20 and 30 plants).

Finally, we did the same analysis for several system configurations. The charts below provide the LCOW for two configurations:

Configuration 1: A wave driven desalination system using electricity as energy medium (Figure 33)
Configuration 2: A wave driven desalination system based on hydraulic power only (Figure 34)

LCOW was estimated for a plant capacity of 2,000 m3/day (annual average) in both case using wave energy level available in Ugu (refer Task 2). Based on this assumption a configuration 1 plant requires 18 WEC to operate while a plant in configuration 2 requires only 15 WEC for the same capacity, resulting in LCOW of \$1.72/m3 for configuration 1 and \$1.53/m3 for configuration 2.

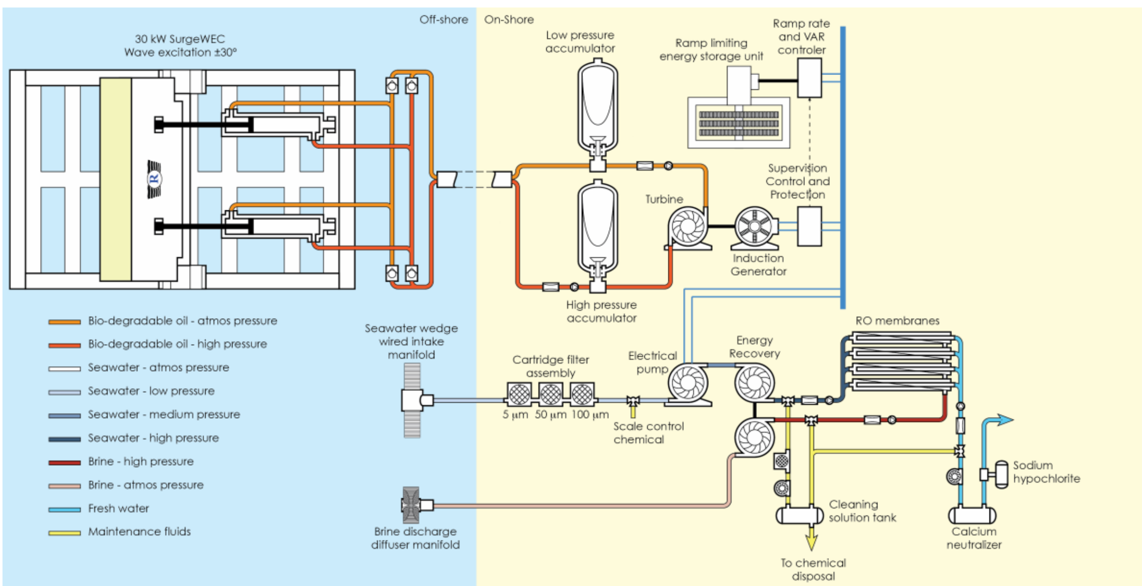


Figure 33. Configuration 1: A wave driven desalination system using electricity as energy medium.

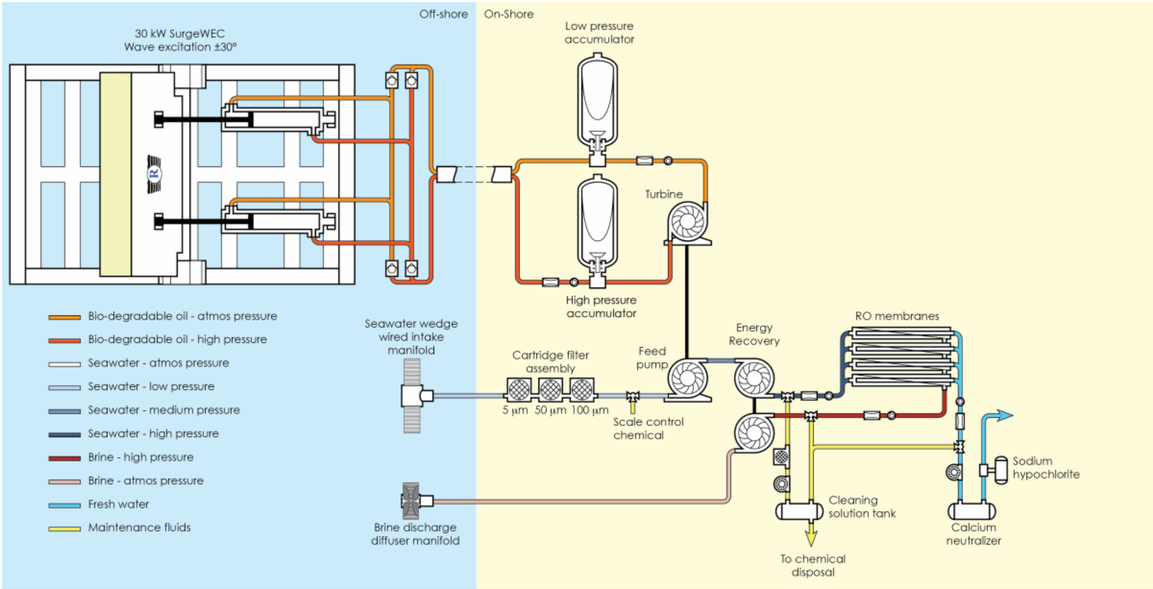


Figure 34. Configuration 2: A wave driven desalination system based on hydraulic power only.

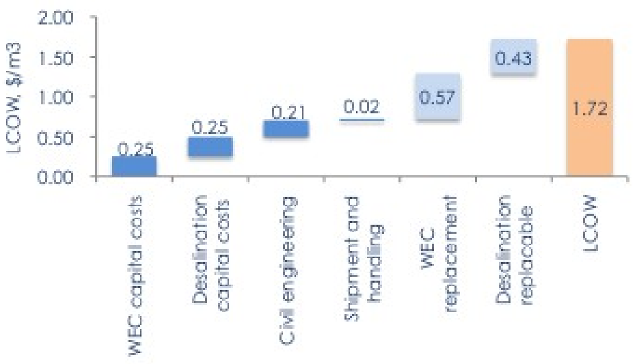


Figure 35. Configuration 1 (with electricity)

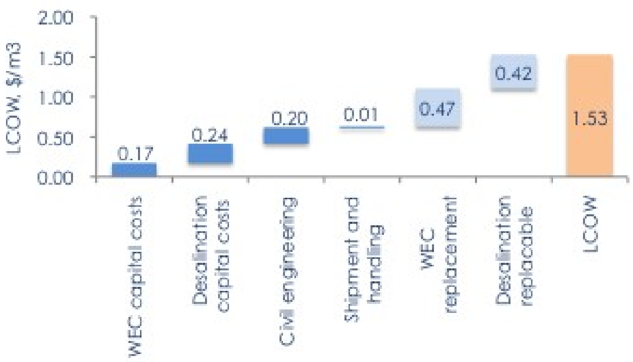


Figure 36. Configuration 2 (without electricity).

Because the current water extraction price in Ugu is \$1.55/m^3, the very first plant installed in Ugu has the potential of be economically viable if we do not use electricity as energy medium. Plant economics will further improve when factoring the learning curve (refer next chart) achieving LCOW as low as \$0.80/m^3 in configuration 2.

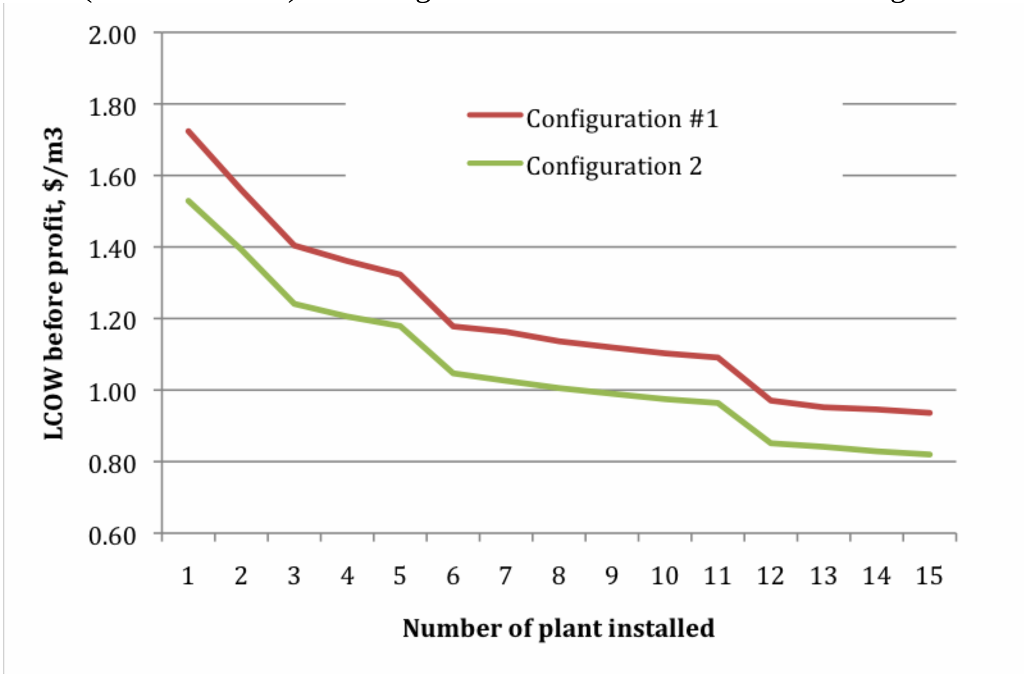


Figure 37. LCOW as function of the number of plant installed.