Final Scientific Report

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1 EXECUTIVE SUMMARY

Ocean wave power can be a significant source of large-scale, renewable energy for the US electrical grid. The Electrical Power Research Institute (EPRI) conservatively estimated that 20% of all US electricity could be generated by wave energy.

Ocean Power Technologies, Inc. (OPT), with funding from private sources and the US Navy, developed the PowerBuoy® to generate renewable energy from the readily available power in ocean waves.

OPT's PowerBuoy converts the energy in ocean waves to electricity using the rise and fall of waves to move the buoy up and down (mechanical stroking) which drives an electric generator. This electricity is then conditioned and transmitted ashore as high-voltage power via underwater cable. OPT's wave power generation system includes sophisticated techniques to automatically tune the system for efficient conversion of random wave energy into low cost green electricity, for disconnecting the system in large waves for hardware safety and protection, and for automatically restoring operation when wave conditions normalize.

As the first utility scale wave power project in the US, the Wave Power Demonstration Project at Reedsport, OR, will consist of 10 PowerBuoys located 2.5 miles off the coast. This U.S. Department of Energy Grant funding along with funding from PNGC Power, an Oregon-based electric power cooperative, was utilized for the design completion, fabrication, assembly and factory testing of the first PowerBuoy for the Reedsport project.

At this time, the design and fabrication of this first PowerBuoy and factory testing of the power take-off subsystem are complete; additionally the power take-off subsystem has been successfully integrated into the spar.

2 COMPARISON OF ACTUAL ACCOMPLISHMENTS TO GOALS AND OBJECTIVES

OPT's Wave Power Demonstration Project at Reedsport, Oregon meets the objectives of the Wind & Hydropower Technologies Program, one of the ten EERE Programs, which works to increase the use of domestic wind and water resources for electric power generation in order to stabilize energy costs, enhance energy security, and improve our environment.

The goal of the Wave Power Demonstration Project at Reedsport, Oregon is to demonstrate wave power as an attractive electricity production option for the twenty-first century by meeting the following objectives:

- Construct the first utility scale wave power project in the US at Reedsport OR based on OPT's PowerBuoy® technology
- Demonstrate the benefits of wave power as an innovative technology that adds diversity to the nation's energy supply
- Demonstrate wave power as a cost-competitive technology
- Demonstrate the environmental advantages of wave power over other forms of energy: no exhaust gases, no noise, minimal visibility from shore and hence minimal visual pollution, and safe for sea life

Funding from this first DoE grant was focused on the completion of OPT's first utility-scale PowerBuoy in the United States which will lead to the launch of PowerBuoy commercial wave energy at Reedsport Oregon in a subsequent phase of the program. Accomplishments under this effort include:

- A Reedsport site survey and trade studies were conducted to determine the optimum configuration of the PowerBuoy system and model the predicted electrical power output of the system. These studies drove the structural, braking, mooring, and PTO requirements of the PowerBuoy.
- The overall PowerBuoy system design was completed based on reliability, survivability, fatigue requirements and slam loading. A detailed design package was released for quotation and subsequently for manufacture.
- The PowerBuoy structure, which includes the float, spar, truss assembly, and heave plate, was fabricated by an experienced, qualified Oregon-based fabricator.
- Floating Gravity Based Anchors (FGBA) were procured and transported to the Coos Bay Oregon deployment site.
- The auxiliary surface buoys for the anchor/mooring system were fabricated by an experienced, qualified Oregon-based fabricator.
- A site for the On-Shore Station, which houses the supervisory control and data acquisition (SCADA) system used for data collection and control and the grid connection equipment, was selected.
- The SCADA system equipment, which provides reliable data collection, monitoring and remote operation of the Reedsport PowerBuoy system, was procured, configured and tested.
- Based on OPT's unique design, the PTO, power conditioning and control systems components and sub-assemblies for the PowerBuoy were assembled and pre-tested for system performance at OPT's Pennington, NJ factory.
- Upon successful completion of the PTO factory testing, all PowerBuoy power conversion equipment was shipped to the Oregon-based fabricator's site.
- The PTO, conditioning and control systems components and sub-assemblies were integrated with the PowerBuoy structure at the Oregon-based fabricator's site.
- The fully integrated PowerBuoy subsystems were tested to insure the integrated system was functionally performing as expected prior to final structural assembly and deployment, which would occur on a follow-on effort.

OPT received approval from the U.S. Federal Energy Regulatory Commission (FERC) for the full build-out of a planned 1.5 megawatt, grid-connected wave power station. This was the first FERC license for a wave power station issued in the United States and provides an important regulatory approval for the deployment of up to ten (10) OPT devices.

The FERC-granted 35-year license for grid-connected, wave energy production follows an extensive process of environmental assessment, notifications to the public, assessment of Federal and State regulations, and consideration of a broad array of comments, recommendations and terms and conditions.

Ocean power provides a predictable and dependable source of renewable energy with no exhaust gases, no noise, minimal visibility from shore, and is safe for sea life. In addition, ocean power is easily fed into the electric grid, as previously demonstrated under OPT's US Navy project at Marine Corps Base Hawaii, and can provide a load factor of 30-45% compared to solar and wind load factors of 10-35%, which indicates that wave power can be made cost competitive at the utility scale in large production quantities.

3 SUMMARY OF PROJECT ACTIVITIES: DESIGN AND FABRICATION

3.1 Requirement & Specifications

3.1.1 STUDY TO DEFINE SURVIVAL METOCEAN CONDITIONS

Survival loads for the structure and mooring were based on a defined set of MetOcean conditions for Reedsport, Oregon, namely a 100-year storm (i.e. probability of occurring once in a 100-year period). The 100-year wave height, period, and direction were defined based on a long record of wave observation from NDBC buoys near Reedsport. The study was conducted by Dr. Peter Ruggiero at Oregon State University under subcontract to OPT and concluded that the 100-year return period wave was characterized by a significant wave height of 14.74m and peak wave period of 17.5 seconds. The contractor also estimated the wave climate for Reedsport, a necessary input for power projections and fatigue analysis, based on the same dataset.

The 100-year current, wind, and tidal range were defined based on available local measurements and model outputs. The study was conducted by Marine Innovation & Technology under subcontract to OPT and concluded that the 100-year return period wind speed was 23.4 m/s, the 100-year current velocity at the surface was 3.7 (3.4) knots in ebb (flood) tide, and the sea surface elevation ranged from -2m to 1.65m due to tides on a 100-year return period. Both contractors' reports also included the direction of the 100-year wave, current, and wind, which is required in order to estimate the vector sum of environmental forces on the PowerBuoy and its mooring system.

3.1.2 SITE POWER PROJECTIONS

An existing proprietary OPT model was developed prior to this project. The model was used to estimate the expected PB150Lite power output in Reedsport, Oregon. Simulations were performed for a wide range of sea states. At each sea state, the model output included a time series of mechanical power which was time averaged. Power values for different sea states were tabulated to obtain a power matrix. To obtain the annual average power at a site, the power matrix is weighted by each sea state's probability of occurrence and then summed. Both annual and monthly power averages can be obtained in this fashion. The model does not simulate the efficiency of the Power Takeoff in going from mechanical to electrical power. Instead a reasonable efficiency was assumed based on bench test and laboratory testing of the Power Takeoff.

An example power projection for Reedsport, Oregon is shown in Figure 1. Power projections were made to anticipate the PowerBuoy's performance when deployed at the Reedsport site as well as economic model metrics such as the levelized cost of energy (LCOE).

Figure 1: Monthly average electrical power out of PB150 Lite at Reedsport, Oregon. The annual average value is indicated at right.

3.1.3 STRUCTURAL REQUIREMENTS

OPT first designed the PB150 for deployment in EMEC, which is a wave power hub near the Orkney Islands, Scotland. The initial PB150 buoy structure was certified by Lloyd's Registry, which has a minimum 100-year peak loading safety factor requirement of 1.11¹. Although this safety factor is acceptable for Lloyd's Register, OPT decided that a minimum safety factor of 1.5 should be required for a test article design. Therefore, the PB150 structure for both Scotland and Portland, Oregon deployments would be modified to increase the safety factor to the OPT requirement; this resulted in what is collectively called a PB150Lite (PB150L) design, specifically a PB150B1 constructed for Scotland, and a PB150B2 constructed for Oregon.

Since the loading on the PowerBuoy is dominantly driven by the float and heave plate diameters, both diameters were reduced by a third from the original full size PB150, which contained an 11m float diameter and a 13m diameter heave plate. The hydrodynamic axial load is proportional to the ratio of the diameters raised to the third power, per Froude scaling.

Consequently, the float diameter was reduced from 11m (PB150 Full Size) to 9.5m, and the heave plate diameter reduced from 13m (PB150 Full Size) to 11m.

The loading is based on the 100-year storm in the Orkney Islands, Scotland, which is considered one of the harshest wave environments in the world based on a variety of global sites that have been analyzed by OPT to date. All structural members in the PowerBuoy are analyzed using the Finite Element Analysis (FEA) method ascribed in DNV RP-C203². All geometry shall be analyzed in its final configuration with minimal simplification.

3.1.4 BRAKE STUDY

The PB150B2 has a brake intended to allow the system to safely survive storm conditions. A study using a commercial software package, OrcaFlex, was conducted to determine (1) the power dissipated in the brake and (2) the number of

hardstop impacts while braked. Both quantities depend on the chosen braking force. In the model study, a representation of the PB150B2 geometry with a braked Power Take-off (PTO) was subjected to survival sea conditions at Reedsport. Figure 3 is a screenshot showing the overall model setup. Simulations were run for different choices of braking force.

Even with a brake, some hardstop impacts can occur during storms due to brake slippage. The impacts are acceptable if the impact velocity can be withstood by the hardstop (bumper). For the different choices of braking force, the maximum hardstop velocity was determined from simulated time series of float position and velocity. The model study results were then used to generate a brake specification.

As a result of the above study, the braking force requirement was chosen to give a 25% buffer above the minimum required rating, as well as a 30% buffer below the rated load of some of the affected mechanical components of the PTO. Additionally, this study suggested that the power dissipation effects are sensitive to the applied brake force. To ensure accurate applied brake force, the brakes were calibrated.

3.1.5 PTO SPECIFICATION

OPT performed trade-off studies to determine the optimum size and number of generators. OPT found that a PTO system with eight generators is optimum. Fewer than eight generators results in large, expensive generators that would not fit the diameter of buoy spar. More than eight generators results in smaller generators that overall were more expensive and would not fit the length of the buoy spar. An input to these trade-off studies was the PTO force and velocity requirements. Such requirements are shown in Figure 2 showing conditions D and E (energetic wave conditions) that occur infrequently. These conditions, drive the peak ratings of the PTO and generator components. Conditions A, B and C occur more frequently and drive the generator efficiency requirements.

Figure 2: PB150 and PB150L PTO power and damping requirements.

From the hydrodynamic analyses, the PTO requirements can be derived.

The large wave day requirements drive the peak torque, velocity and power ratings of the PTO components. Short-term peaks can be handled using the thermal mass of the components. For system cooling requirements, the large wave day continuous requirements drive the design. Given that the large wave days occur infrequently, PTO efficiency is less of a concern than on typical days. For this reason “average” wave day conditions are specified in addition to the large wave days. Thus, large wave day conditions drive component torque and velocity ratings and average wave day requirements drive component parameters that effect system efficiency.

The starting point for the development of PB150B2 electrical system requirements was the PB150B1 (Scotland deployed PowerBuoy) electrical system specification. The PB150B1 system AC grid is three-phase 575VAC (a European standard). The AC grid voltage requires DC link voltages of at least 850VDC. This DC link voltage requires the generator instantaneous peak voltage to be well below 850V (or 600 VAC). For this reason the PB150B1 generator peak RMS voltage was set at 575V.

3.1.6 MOORING STUDY

The commercial software OrcaFlex was used to define the PB150B2 mooring loads, which are needed for (a) mooring component selection and (b) design of the structures affected by the mooring, such as the mooring lugs and their connection points on the spar. A representation of the PB150B2 geometry with accurate mass properties and dimensions was created in OrcaFlex. Figure 3 shows the mooring representation in OrcaFlex; each component shown is composed of many model elements.

Figure 3: Plan and elevation views of PB150B2 mooring system

In the mooring study, the baseline mooring was OPT's default mooring design consisting of 3 mooring legs with subsurface buoyancy and seabed anchors. For the baseline model, standard mooring lines and components were chosen based on manufacturer catalog data. The model was set up to generate a time series of waves and currents characteristic of the defined survival MetOcean conditions. The relative direction between the waves and currents was based on the defined survival conditions.

Additional studies varied the mooring lengths and components. The time series of simulated mooring loads were used to identify the expected highest load in 3 hours' duration of the 100-year storm. Ten 3-hour simulations were performed, and the maxima from each simulation were averaged with the goal of increasing the robustness of the estimate.

3.2 Detailed Design

3.2.1 STRUCTURE

This section will summarize the results of the structural design.

3.2.1.1 STRUCTURAL ANALYSIS METHODOLOGY

(a) FEA Method

Based on FEA calculations of stress, hot spots are identified and studied. The mesh near the hot spots consists of elements with sizes meeting the requirements of at most $2t \times 2t$ in critical bending stress directions, but ideally less than $t \times t$. The hot spot stress is derived by linear extrapolation.

Figure 4: Example of Hot Spot 1st Principal Stress

(b) Survivability

Buoy integrity is evaluated using hot spot stresses considered to occur in the high stress regions that will fail first by either yielding or fatigue. Despite higher conservatism than using field stress, hot spot stress is used due to the fact that all the critical locations have high stress caused by stress concentrations and complicated geometry, which leads to unclear definitions of field stresses per FEA results.

Survivability is assessed based on the maximum load seen by the component during a 100 year storm. The von Mises hot spot stresses should be less than the yield strength of the material with a factor of safety of at least 1.11^1 for certification; however, OPT required a higher safety factor. The stresses are compared to the used material properties.

(c) Fatigue

While survivability is assessed independently from the loading cycle, fatigue accounts for the loading cycles by calculating the fatigue utilization at each stress fatigue range / cycle count interval.

Stress considered in this calculation is the 1st principal stress. If the stress range is below the endurance limit, the joint will be considered to be free of fatigue. However, if any load cycle induces a stress greater than the endurance limit, a detailed fatigue calculation is assessed². The stress fatigue range used for this fatigue assessment is based on the hydrodynamic loading range per the linear 1st principal stress ratio to applied design or unit loading.

Figure 5: Example Cycle Count Histogram

The load range and cycle count are based from experimental data. The “Baseline Stress Ratio” is simply the max hot spot stress from the analysis divided by the applied load.

$$BaselineStressRatio = \frac{\sigma_{hot_spot}}{F_{applied}}$$

Since the FEA is a linear elastic calculation, multiplying the *BaselineStressRatio* by the *MomentFatigueRange* yields the stress range that corresponds to the particular cycle counts.

The *Fatigue Life Cycle Limit* can be calculated at particular stress ranges that correspond to those in the histogram shown in Figure 5. Based upon the ratio between the *Fatigue Life Cycle Limit* and the expected cycle count, the *Fatigue Utilization* is calculated. Summing the *Fatigue Utilization* over the stress range spectrum yields the *Total Life Utilization*.

(d) Slam Loading

Survival wave tank tests were conducted in 2008 by OPT at a qualified wave tank facility, and provided the structural loads used in the PB150B2 design. During the wave tank tests, ringing was observed during float slamming onto the free-water surface. The concern is that ringing may accumulate vibration cycles with or without perfect resonance and lead to early fatigue damage.

The maximum water added mass effect for a panel is up to 1000%³. The slam pressure rising and dying time is observed as 0.12 second and 0.45 second with linear profiles, respectively. Therefore, the Duhamel’s integral approach to considering tapering pressure induced vibration is taken to calculate the vibration amplification factor with respect to the quasi-static pressure. Given the complication and uncertainty of the damping ratio of the structures, the Duhamel’s integral excludes the damping effect and leads to more conservative results.

The amplitude of the vibration can then be compared with the stress induced by that vibration. If the stress is within the endurance limit of the structure, there should be no fatigue damage.

Overall RESPONSE

$$\text{amp}_{\text{overall}}(t) := \text{amp}_{\text{rise}}(t) + \text{amp}_{\text{fall}}(t)$$

Figure 6: Response plot of slam event on float bottom

The deformation oscillation is $\pm 3.0\%$ of the magnitude of quasi static deformation. The slam force induced vibration does not concern the float integrity.

3.2.2 MECHANICAL PTO

The PTO is a scaled up version of a previously designed system that OPT had success with, specifically in the 10kW PowerBuoy deployed off the coast of Hawaii from 2008 to 2010. The basic concept is the force from the float is input into the spar via a thrust rod that drives the linear to rotary motion mechanism, which in turn drives the generators.

The interface between the thrust rod and the linear to rotary motion converter is designed to ease the assembly process. The design allows a pin to be mechanically compressed for insertion through a clevis and rod end and then mechanically expanded to obtain an interference fit between the pin and rod end.

Compliant bearing systems are used to compensate for installation tolerance and operational deflections during high load events. The design thereof follows the logic shown in Figure 7.

Figure 7: Design Logic for Component Selection of the Compliant Bearing Mount

Figure 8: Stress Plot of Compliant Bearing Mount

The PTO linear to rotary motion converter system is designed for infinite life based on operational and survivability loading profiles.

The HPUs (hydraulic power units) for the brake systems, used to lock the PTO in case of severe storm conditions, are designed to be fail-safe. If power or control signal is ever lost to the HPU, it will apply and hold pressure to the brakes until power and control are restored. This feature is very beneficial because, if power or control is lost, the buoy could have a catastrophic failure if allowed to free-wheel. The HPU system works by maintaining a large reservoir at high pressure. The valve between this reservoir and the brakes is normally-closed. Powering the valve opens the valve and the high-pressure reservoir is disconnected from the brakes allowing the PTO to move freely.

3.2.3 GENERATORS

Preliminary design of the generators started with a search for off the shelf high-power, low-speed, high-torque motors.

Various suppliers that make high-power, high-torque machines in the range of interest were approached. Specifications and non-binding RFQs were sent to these manufacturers. The field was quickly narrowed to a most competitive solution in terms of size, weight, torque, speed, efficient and other performance parameters, and cost.

Figure 9 shows representations of the downselected generators inside the spar. As shown, both generators could be accommodated in the spar envelope.

Figure 9: Siemens and Parker generator options, shown inside buoy spar

Figure 10: Down-selected torque generator/motor

Before the final generator supplier could be selected, it was necessary to quantify more rigorously the efficiency of the generator options. Power losses were calculated as follows:

- Winding loss

$$P_w = 1.5 \cdot I^2 \cdot R_{WH}$$

I = generator RMS current (in Arms, from calculations)

R_{WH} = winding hot temperature resistance (in ohms, from vendor)

- Friction loss

$$P_F = T_F \cdot \omega$$

T_F = static friction (in Nm, from vendor)

ω = angular speed (in rad/s, from calculations)

- Viscous damping loss

$$P_{DV} = K_{DV} \cdot \omega^2$$

K_{DV} = viscous damping (in Nm/rad/s, from vendor)

ω = angular speed (in rad/s, from calculations)

OPT used two methods to calculate efficiency, with power losses computed as described above:

- Method 1
 - Day peak and day continuous RMS values for torque, current, and angular velocity plugged into power losses equations
- Method 2
 - Time series torque, current and angular velocity values plugged into power losses equations to compute instantaneous losses, then time-series average power losses used to calculate efficiency

Method 1 is quicker than Method 2. Method 2 is more accurate than Method 1. During the preliminary design phase both analysis methods were used, with the expectation that Method 1 would be found to be accurate enough for all future design and analysis activities. The results of the two methods indicated generator efficiencies in the range of 85% to 95%.

The results of the Method 1 analysis identified the most efficient generator solution. A Siemens product was procured and used in the final design. Figure 11 shows the PTO generator reference torque and speed profile for a large wave day.

Figure 11: PB150B2 "Large Wave Day" PTO generator reference torque vs. speed

3.2.4 GENERATOR DRIVES

Generator drives are needed for several reasons. First, the torque of the generators must be regulated in order to extract the maximum power from the waves. Second, the highly variable AC power must be converted to DC so that the energy can be stored and released by large capacitor banks, so the variation in power is not introduced to the power grid. The generator drives perform the functions of generator torque control and AC-to-DC conversion.

As described above, the design evolved to one with eight generators. OPT evaluated several configurations of drives to interface with the eight generators:

- 8 generators and 8 drives
- 8 generators and 4 drives
- 8 generators and 2 drives

The third option results in the lowest drive cost and hotel load. This approach would not assure that each generator provides the exact same torque, unless the generators were wired in series. This approach would require each generator to handle high current. To assure equal torque of all generators, the first option is recommended, so that is the approach that was selected.

As indicated above, a Siemens generator/motor was selected for the PB150B2 application, due primarily to their higher efficiency and overall performance of the application at hand. With the generator selected, it was then necessary to select the drive device that would regulate the torque of each generator. For various reasons including cost, overall value add and technical support services, OPT selected a Siemens drive, shown in Figure 12. Power loss and efficiency data for the Siemens drives indicate efficiency up to 97% under the specifics of the application of interest.

Figure 12: Siemens S120 generator drive option.

3.2.5 ELECTRONICS AND CONTROLS

The design of the electronics/electric system of the PTO began with an analysis of lessons learned and particularly of what worked well in our previous PowerBuoy deployments and what required a redesign either to account for the new PTO linear to rotary motion conversion system approach or to accommodate the higher power output of the PB150B2. Since the PB150B2 is a dual PTO system it made sense to extend the dual PTO concept to the electrical circuit including the controls. In the PB150B2, each PTO has a dedicated controller allowing for graceful degradation where a single PTO controller failure will not result in the full buoy shutdown but in a sustained operation a single PTO.

This design approach was also incorporated into the buoys communications network. The internal Ethernet network includes redundant network switches and redundant Ethernet cables. At the sensor level, critical signals such as float position and velocity are measured with redundant sensors. The critical signals are crossed between PTO controllers such that a loss of a critical signal will not take down both PTOs.

Each motor has its own motor drive so that a failure of a single motor drive will not significantly degrade the buoys output. The ultra-capacitor energy storage bank and the Active Front End inverter were scaled up from previous PowerBuoy designs. The control system hardware and DAQ panels also worked well and were originally designed to be configurable and scalable so it made sense to use those designs.

The cabling system was designed and the cable assemblies manufactured by OPT. OPT learned from previous buoy fabrications that cable systems utilizing connectors as opposed to hook-up wire was advantageous in the assembly and maintenance processes.

The overall electrical design was divided logically into functions that could be realized on separate individual panels. This helped expedite fabrication, testing and the final PTO installation.

3.2.6 MOORINGS

Based on the mooring study and resulting mooring loads, the design of the mooring and anchors was carried out. The anchor design consists of three mooring lines at 120° spacing, coupled with Auxiliary Subsurface Buoys (ASBs). Each line is

anchored with a Floating Gravity Based Anchor (FGBA). This design is suitable for the sandy seabed floor around Reedsport, OR.

3.3 Procurement, Fabrication, and Assembly

3.3.1 STRUCTURE PROCUREMENT, FABRICATION, AND ASSEMBLY

OPT completed the detailed design of the complete PowerBuoy system during the third quarter of 2009. Small design details were revised as OPT worked with the selected metal fabricator, in an effort to accommodate any manufacturing constraints and/or opportunities for cost reduction.

Figure 13: Spar fabrication at OIW

During the first quarter of 2009 OPT contacted and visited a number of Oregon-based steel contractors. OPT selected Oregon Iron Works (OIW) to perform the mechanical fabrication of the PB150B2 PowerBuoy which included the float, spar, tow-out tank, truss and heave plate. The purchase order for this work was issued to OIW in November of 2009.

OIW began work on the buoy in November of 2009 beginning with the fabrication of the spar ribs and sections of the heave plate. OIW made

excellent progress through the first quarter of 2010 and was nearly complete with the fabrication of the spar, heave plate and float, including the final inspections of the components from their QA/QC department. Fabrication of the truss assembly began the first week of May 2010. The bridge fabrication followed.

OIW completed the fabrication of the PB150B2 heave plate, truss, spar lid and float by the end of June 2010. Both the heave plate and float were pressure tested according to OPT's test requirements. The two separate tests were witnessed by OIW's QA/QC department as well as by OPT's onsite representative. Both tests passed without issue. The float was also vacuum tested by OIW to OPT's test requirements.

Again, both were witnessed by OIW's QA/QC department as well as by OPT's onsite representative. The float passed the vacuum test without issue.

Figure 14: Heaveplate fabrication at OIW

The heave plate, truss, spar lid and float were painted in July of 2010 and staged for final assembly. The fabrication of the bridge assembly and main struts were completed and painted in August 2010.

Figure 15: Float halves complete, painted, and undergoing final alignment check

Figure 16: Truss attached to completed heaveplate at OIW

Figure 17: Spar lid nearing completion at OIW

Figure 18: Buoyancy collar complete

OIW continued work on the spar throughout the third quarter of 2010 when the full spar was completed.

Figure 19: Bridge complete and painted

The spar went through OIW's QA/QC procedure and was reviewed by OPT's onsite representative. The spar met all of the QA/QC requirements and was then moved for final blast and paint.

The heave plate, truss, spar lid and float were painted August of 2010. They were inspected by both OIW's QA/QC department and OPT third party independent inspectors. All items passed the inspection requirements were stored until needed for assembly.

OIW completed all tasks contracted by OPT during the fourth quarter of 2010. All of the fabricated buoy components were stored on OIW's grounds.

3.3.2 MOORING PROCUREMENT AND FABRICATION

The anchor/mooring subsystem takes advantage of Floating Gravity Based Anchors (FGBAs). Contractors for the fabrication of the FGBAs were identified.

An RFQ package for the fabrication of the Auxiliary Subsurface Buoys was prepared and sent out for quote in mid-October 2010. The RFQ included the fabrication of the ASBs as well as stands required to store the ASBs prior to deployment. The bids were received during the early part of November 2010 and were reviewed by the procurement, mechanical and marine operations departments to determine which were commercially and technically acceptable. The bid from American Bridge was the most commercially and technically acceptable.

A cost analysis was performed to determine if it was more cost effective to fabricate new FGBAs in the Portland, OR area or to ship already constructed FGBAs from the UK. It was determined that the cost difference between fabricating and shipping was large enough that it would be prudent to ship the

Figure 20: FGBA loading onto Jumbo Shipping vessel in Scotland ready for shipment to Coos Bay OR

FGBAs from the UK to Coos Bay, OR. The FGBAs were loaded at Inverness, Scotland and were received at Coos Bay, OR the first week of May 2010.

Figure 21: ASBs (3) complete and on barge ready for delivery to Coos Bay

American Bridge began the fabrication of the ASBs the first week of January 2011. Within the first few weeks they completed the fabrication of all of the keel beams and the domes for the ASB. Next they fabricated the outer shells, all of the internal piping and the ASB headers. Interim weld and dimensional inspections were conducted throughout the build process. All inspection reports confirmed that American Bridge was fabricating the ASBs per OPT specifications and requirements.

Bexco completed the fabrication of all of the mooring ropes for the spar, ASBs and the FGBAs. Third party inspectors of the mooring lines found them to be technically acceptable, so the ropes were crated and shipped directly to Coos Bay, OR the second week of May 2011.

Bexco's sub-vendor completed fabrication of the various spools, tri-plates and interconnectors the first week of May 2011. Bexco submitted fabrication inspection reports for the interconnectors which were reviewed by OPT and found to be technically acceptable.

Figure 22: All three FGBAs on-site in Coos Bay

After the FGBAs were received in Coos Bay, OR in May of 2011, American Bridge was awarded the contract to attach the FGBA mooring clevises onto the FGBAs. The attachment of the clevises to the FGBAs was completed March 2012.

3.3.3 PTO PROCUREMENT, FABRICATION, AND ASSEMBLY

The physical fabrication of the PTO mechanical components, such as the motor/generator table, and the PTO table turner, were released in February 2010 to various vendors to solicit competitive bids. Purchase orders were awarded to the successful bidders, and fabrication began in March 2010. Third party inspectors were hired to conduct weld and dimension inspections of each of the fabricated components and ensure compliance with OPT specifications.

Figure 23: PTO assembled and ready for test at OPT

The PTO motor generator table was delivered to the OPT facility in November 2010 after final inspection. Once received, the table was populated with the motors, brakes as well as all of their electrical components. The work was completed mid-March, 2011 after which, the table was handed over to the engineering department so that PTO testing could commence.

3.3.4 TESTING OF PTO

3.3.4.1 OBJECTIVE

Figure 24: Fully Tested PTO packaged and leaving OPT, bound for integration into spar at OIW

Testing of the PB150B2 PTO was completed at OPT NJ in order to confirm that the system performed as specified and to determine the PTO's mechanical to electrical efficiency. The PTO testing included thorough testing of each individual sub-assembly as well as full system testing.

PTO sub-assemblies were tested upon completion. Tests included both design verification and manufacturing quality assurance tests. The completion of sub-assembly tests helped expedite the system level testing.

The objectives of the PTO System Level Testing included: (1) verifying the design and fabrication of the PTO under loaded conditions using a test setup specifically designed for PTO testing, (2) testing any subsystems that had not been fully verified at the subsystem testing level, (3) testing the integration of subsystems, (4) testing the system software functionality.

3.3.4.2 SCOPE OF WORK

The PTO successfully completed endurance test cycles during the last quarter of 2011. The final set of test cycles was conducted without incident or issue. A review of the results of all of the test procedures and specifications was conducted between all of the OPT department managers.

The PTO was then prepared for shipment in April of 2012, along with all of its ancillary equipment, and shipped cross-country to its final insertion site in Vancouver, WA. The shipment occurred without issue and the equipment was also successfully unloaded at the insertion site.

3.4 Final PowerBuoy Assembly and Readiness

OPT determined that OIW would be contracted to install the PTO into the spar as they offered the best facility and technical team to conduct this high precision work. The contract for the buoy final assembly was awarded to Vigor, under a follow on DOE award, as they had the best facility to assemble the buoy's large components.

The PTO arrived at OIW the third week of May 2012 and the insertion process began. Preliminary testing began on the PTO to ensure that it survived the 3,200 mile journey across country. Tests were conducted by the electrical and mechanical teams on the PTO, which met all of the requirements. The operations team also did a physical inspection of all of the PTO components and agreed that the PTO was fit for installation.

Figure 25: PTO Arrival and Preliminary Testing

4 SUMMARY OF PROJECT ACTIVITIES: SPAR ASSEMBLY & INTEGRATION OF PTO

The Power Take Off system (PTO) for the PB150B2 PowerBuoy was successfully inserted and aligned into the spar at Oregon Iron Works (OIW). The spar assembly underwent final assembly and testing at OIW, the successful completion of which concluded the work performed by OIW on the project.

4.1 Spar Assembly Complete

Once the Spar Assembly was completed at OIW the spar was placed on a barge and transported to the Vigor Marine facility for final Buoy Assembly.

Figure 26: Spar assembly 100% complete, being moved for final buoy assembly at Vigor marine

4.1.1 SHORE STATION SETUP

Figure 27: Lighthouse museum used as shore station

The on-shore station procurement and assembly followed the completion of the detailed design task. The on-shore station houses the supervisory control and data acquisition (SCADA) system used for data collection and control. The system was configured to provide reliable data collection, monitoring and remote operation of the Reedsport buoy from OPT's base in Pennington, New Jersey.

Figure 28: View from shore station, red arrow indicates buoy deployment site

In addition, the SCADA system is used during land-based testing.

A number of shore station locations were identified and then narrowed down to a single location, the Coos Bay museum/light house. Engineering visited the location and found it to be technically acceptable for communications between the buoy and the station. Based on the recommendation of the procurement and operations teams, in August 2012, OPT entered into an agreement with the museum for the necessary space required for the electrical and radio equipment.

The radio equipment to be used to communicate with the buoy was tested and found to be technically acceptable. The radio components were shipped to the PTO insertion site waiting to be installed into the on-site shore station.

The shore station equipment includes a standard computer running the HMI screens. This computer communicates directly with the PowerBuoy control system to display real-time data and allow for Operator control. A desktop computer is provided for troubleshooting if required and is also used as a backup if the HMI computer fails.

Additionally the shore station includes a data server computer running Windows Server operating system. This computer is used to retrieve and store the high-speed buoy data in a SQL database. The shore station SQL data is subsequently

transferred to the OPT Central server over the Internet connection using standard SQL replication techniques or by running another version of data retrieval software on the OPT server.

5 WORKS CITED

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