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1 INTRODUCTION

Columbia Power Technologies, Inc. (C·Power) is developing a direct drive, rotary (DDR) wave energy converter (DDR-WEC) for utility-scale power applications, known as the StingRAY. The DE-EE0006610 Project objectives are to improve the overall Power-to-Weight Ratio (PWR) and decrease Levelized Cost of Energy (LCOE). This will be achieved by decreasing capital expenditures (CAPEX), reducing structural mass, and increasing energy production performance.

A major advancement of the StingRAY hull structure was progressed from concept to final design under this Project. This next-generation hull architecture significantly increases the power performance of the WEC, while reducing the complexity and cost of the WEC system through efficient use of structural and power generation components, along with simplified component geometries aimed at reducing manufacturing costs. The prototype design was progressed from concept to final design with structural drawings, in preparation for a planned deployment at Wave Energy Test Site at Marine Corp Base Hawaii in Kaneohe Bay.

A mixed materials approach to further structural optimization was developed under this Project and validated with extensive laboratory structural testing. This approach substitutes fiber-reinforced plastic (FRP) for steel where appropriate. The benefits of steel are maintained where most useful, for instance at structural joints where the stiffness of steel is required, and the complex geometry is more readily fabricated with steel. However, there are structural spans whose simple shapes are readily fabricated with mandrel-wound FRP and where significant cost and weight savings can be found. An adhesive, double lap shear joint is used to join the FRP and steel subcomponents.

The purpose of this document is to outline plans for integrating Project improvements into C·Power's WEC technology.

2 PROTOTYPE H2 WEC DEVELOPMENT AND DEPLOYMENT

Development of the prototype H2 structural design was a three-stage process: transformation from H1 design to H2 concept; progression to prototype H2 structural design (within this Project); and conversion from structural arrangement to fabrication drawings.

2.1 H2 Concept and Structural Design

At the time of C·Power's DOE FOA 1310 proposal, in advance of the 6610 Project, a three-body WEC architecture (H1) was employed. Developed under DE-EE0005930 (5930), the H1 was examined for cost reduction opportunities in conjunction with DE-EE0007347 (7347). It was determined the aft float and generator pair were harvesting about a third of the energy captured by the fore float and generator. Further, H1's damper plate, which was to be solid steel, came under scrutiny for its cost and operational challenges it presented to float it during deployment and recovery. The heavy damper plate was replaced with a lighter tank that could use seawater for variable ballasting that could be removed to put the WEC in its transit or towing configuration (ballast tank at the surface). Flooding the variable ballast tanks drops them back down into the water column and allows the H2 to settle into an operational orientation. The aft float was replaced by fixed, highly buoyant cylindrical structures cantilevered aft of the nacelle; these pontoons are strengthened by knee braces extending between the pontoons and ballast tank.

The resulting two-body WEC (H2) offers numerous benefits including lower part count, more efficient use of materials, lower-cost ballast, and increased power performance. The H2 size was optimized specifically the WETS deployment location, resulting in a WEC size somewhat smaller than the H1, yielding decreased CAPEX for the prototype deployment In alignment with the 6610 Project objectives and a desire to capitalize on these technical advancements, DOE and C·Power agreed that the improved two-body H2 WEC architecture should be integrated with the 6610 Project.

2.2 From Structural Design to Fabrication Drawings

Under 7347 the structural design developed in 6610 was converted to fabrication drawings. Although manufacturability was always a prime consideration in design, bringing dedicated fabrication expertise online to create the fabrication drawings introduced additional changes. Accuracy was validated by using the fabrication drawing package to virtually build the WEC in a 3D model.

2.3 Experience and Data from Fabrication, Deployment, and Testing

The WETS H2 prototype WEC will be fabricated at Thomson Metal Fab in Vancouver, WA and transported by barge to Oahu, HI for deployment and testing at WETS. Experience gained in fabrication, transport, deployment, operation, and testing will be invaluable for future design work. The WETS H2 will be fully instrumented and will yield significant data for validation of the Project design (e.g., load cells, strain gauges). An instrumentation plan is being developed under thorough a Small Business Voucher collaboration with NREL that is specifically targeting (though not limited to) data to validate the structural response at joints where fatigue was an issue, and for the float and arms where slamming loads drove the design.

3 H3 DESIGN

The design methodology employed in this Project will be used in the development of the next-generation StingRAY WEC (H3) to be designed for deployment at PacWave-South in Oregon under newly awarded DE-EE0008954 (8954). The mixed materials concept developed in this Project will be explored further in 8954 and incorporated to the degree that analysis indicates support for improved LCOE or other relevant metrics.

3.1 Potential Hybrid Components

Component mass reduction is generally beneficial for the H2 WEC, and 6610 demonstrated potential for component mass reduction using hybrid steel/FRP construction. All else equal, a reduction in component mass will be balanced by an increase in ballast mass to maintain the draft line of the floating WEC. The pitch response of the WEC is generally increased when mass is concentrated in the ballast tank rather than distributed over the WEC, increasing performance. Additionally, reducing component mass eases assembly and transportation logistics requirements. Capital expenditures, and indeed total cost of ownership, will be considered in investigating potential hybrid components.

3.1.1 Pontoons

The H2's pontoons replaced the H1's aft float. They serve to resist generator torque, activate the main body of the WEC in an active pitch motion, and to orient the WEC to the wave direction. These structures are designed to be highly buoyant, and WEC power performance increases as their mass is reduced. These simple, cylindrical structures were the focus of the 6610 mixed materials investigation and will most certainly support an LCOE trade study based on energy extraction relative to cost.

The quadraxial material tested in 6610 was recommended by Ershigs for stiffening details (e.g., hat stiffeners). Stiffening elements, particularly to resist slamming pressures, will be considered for further exploration in H3 design.

3.1.2 Knee braces

There are two knee braces that span the distance between the ballast tank and the unsupported ends of the pontoons. These are cylindrical structures rooted into structural joints at either end. While the effect on performance of knee brace mass changes has not specifically been examined, it is considered likely that reducing their mass will have a beneficial effect on performance. Due to these considerations, it is likely that a knee brace hybrid steel/FRP design similar to the pontoon design developed in 6610 will offer LCOE advantages.

3.1.3 Spars

Similar to the knee braces, the simple cylindrical geometry and perceived advantage of mass reduction for WEC power performance, the spars are prime candidates for a hybrid design similar to that developed for the pontoons under 6610. The lower spar has additional requirements as they serve as variable ballast tanks.

3.1.4 Float

The float is necessarily a less massive component. Power performance is generally improved with a lighter float, though there are limits to this. Furthermore, H2 design indicated a need for a lightweight float to allow for the float return mechanism to drive the float back to the fore position after an overtopping event. These considerations render the float a candidate for hybrid construction.

However, given the dynamic loads, the float is subjected to it is unlikely that the arms or the connection to the arms could be cost-effectively fabricated from FRP. Also, slamming loads would certainly require internal stiffening; the prototype H2 float design includes closely spaced bulkheads along with relatively thin shell to handle the loads and keep the weight down. Another possibility to consider is a steel shell with adhesively bonded FRP stiffening elements (e.g., bulkheads, hat stiffeners).

3.1.5 Nacelle

To maintain tolerances and resist generator torque the nacelle section is anticipated to be a steel shell. However, with improved understanding of adhesives used to bond composites to metals the most cost-effective construction may be a combination of steel plate with FRP stiffening ribs (similar to what was discussed above for the float). Potentially an infused extrusion process could be used to fabricate the stiffening ribs economically. A slow curing matrix may simplify final installation. The quadraxial reinforced composites may be cost advantageous stiffeners for bulkheads and structures.

3.1.6 Power Take-Off

The power take-off (PTO) is protected inside the nacelle. There are three major components to consider: the shafts, the rotor, and the localized airgap reduction system (LARS).

Considering the torque that the shafts must carry, FRP is not an option; the section thickness required results in a costly component. The LARS components may benefit from FRP construction, but don’t lend themselves to the metal/FRP interfaces examined in this project. Likewise, the rotor construction would generally not benefit from techniques researched in this project.

3.1.7 Ballast Tank

The ballast tank is currently a shape that is advantageous to mandrel winding. However, FRP is not advantageous for this component as reducing ballast tank mass is not advantageous. The likely alternate material for the ballast tank is structural concrete.

3.2 Fabrication

During the fabrication of the test articles, it was evident FRP is a challenging material to create precision shapes without costly tooling. Machining is difficult and often the uniformity of the material can vary making it challenging to design engineered scrap (the portion that is cut away and discarded) into these components. FRP can be molded into a specific shape but at the cost of sacrificing the finish of the working side and the costly tooling introduces substantially greater wear on cutting tools as compared to aluminum or even steel.

3.2.1 Design for Manufacture

The use of cost-effective lightweight FRP structures requires consideration of the natural variance of minimally controlled FRP fabrication to avoid cost. Metallic mating components must be designed to allow for a larger dimensional variance found in manually fabricated FRP. Components must be designed such that they can be assembled during working times of the adhesive.

3.2.2 Assembly Techniques

Hybrid materials will require considerations by Supply Chain to expand their portfolios. While bonding metallic flanges in FRP in pipeline applications is a standard practice this joint type appears overly costly, requiring both fasteners and seals. The aim of the H3 design will be to leverage the adhesive properties with the dissimilar materials and have the adhesive performing both the attachment and sealing functions.

Automated or semi-automated production of FRP is possible and significantly reduces the labor component of the cost of FRP components. The design of the H2 makes extensive use of cylindrically shaped components to take advantage of this process. A study will be conducted during the H3 design to determine if a hybrid materials design can positively impact LCOE and Total Cost of Ownership (TCO).

3.2.3 FRP Supply chain

The 6610 Project tested filament-wound, hand-laid, and infused FRP manufactured by Corrosion Companies and Ershigs. FRP fabrication is the core competency of these firms. Ershigs has the capability to infuse metallic parts into their products (e.g., bolts), but does not fabricate those parts.

C·Power will continue to develop relationships with these fabricators as the mixed materials design progresses and refines under 8954. As appropriate, they will be consulted for their expertise in FRP fabrication.

3.2.4 Adhesives

The 6610 Project tested adhesives from Huntsman and ITW Performance Polymers. Two adhesives tested met the ultimate and fatigue requirements. Other factors, such as working time, shrinkage, and cost will be examined in greater detail during H3 design. Degradation due to seawater saturation is not fully understood; testing saturated joints was not possible under the 6610 Project, and avenues for testing will be explored moving forward.