Improved Structure and Fabrication of Large, High-Power KHPS Rotors

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1. Executive Summary

The research, development, deployment and demonstration (RDD&D) conducted under this US Department of Energy (DOE) Advanced Water Power Program (AWPP) project has significantly contributed to advancing the design and construction of stronger, larger, and higher-capacity composite turbine blades for use in the nascent Marine and Hydrokinetic (MHK) renewable energy industry. MHK turbines convert energy from water current resources, including tidal and river flows, into electricity.

Specifically, Verdant Power, Inc, working in partnership with the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), and the University of Minnesota (UMN) St. Anthony Falls Laboratory (SAFL), among other partners, used evolving Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) models and techniques to improve the structure and fabrication of large, high-power composite Kinetic Hydropower System (KHPS) rotor blades. The execution of the project was organized by a series of ten tasks with the objectives to: design; analyze; develop for manufacture and fabricate; and thoroughly test, in the lab and at full scale in the water, the improved KHPS rotor blade.

Cost-effective fabrication and manufacture of the composite blade was investigated using US-based manufacturing resources. Also, consistent with the DOE's Technology Readiness Level (TRL) system, the project conducted static and fatigue lab testing of the blades (TRL 5/6) during the first quarter of 2012, followed by full-scale (5m diameter) in-water dynamometry and loads testing of the full rotor assembly (blades and hub) at Verdant's Roosevelt Island Tidal Energy (RITE) Project site in the East Channel of the East River (New York, NY) in September 2012.

The project continued to advance KHPS unit longevity, reliability and cost-effective manufacturing, while maintaining MHK systems as an environmentally-compatible source of clean energy that contributes to the sustainability goals of the DOE and the United States overall. MHK systems provide clean renewable energy utilizing the reliable natural resources of the tides and river currents. In addition to independent generation, MHK systems can also be integrated with other clean energy and energy efficiency systems such as smart grid technology, electric car charging stations, and distributed generation arrangements, among others. Further, the MHK industry is developing scientific, engineering and manufacturing expertise in the United States that can lead to the development of green jobs and export opportunities around the globe.

2. Project Accomplishments

The objective of this project was:

"To design, analyze, develop for manufacture, fabricate and thoroughly test an improved blade structure and concomitant blade design for Kinetic Hydropower System (KHPS) turbine rotors, to allow for stronger, long-lived and more cost-effective rotors for larger sizes and higher power turbines. The performance of the KHPS rotor blade has been successfully demonstrated at the 5m rotor diameter level, but to reach broad commercialization it is necessary to extend the rotors to capture energy from higher water velocities and deeper resources, and to increase its usable life."

To achieve this objective, the project:

- Modeled the flow around the rotor and entire turbine (Tasks 1 and 2);
- Derived the rotor loads and design (Tasks 3, 4 and 5);
- Analyzed the rotor blades and hub (Task 6);
- Fabricated (Tasks 7 and 8) and
- Tested the full-scale blade and hub (rotor) design:
 - in the lab (Task 9) and
 - in the water, with concurrent assessment of environmental compatibility (Task 10).

All objectives were accomplished and have led to significant observations and directions for the future of the KHPS. In summary, with the conclusion of the In-Water Test (IWT) associated with this project, Verdant Power has achieved all of the objectives of designing and assessing an improved structure and fabrication process for larger, higher-power KHPS rotors, with full-scale lab and in-water testing. Results to date indicate that structural integrity, cost-effective fabrication, longevity and scalability targets have been met. As expected, some compromise on hydrodynamic (energy capture) performance was seen due to the structural changes and are attributable to several factors under review; however, the pathway to commercial scalability has been defined and appears achievable. Additionally, advancements in demonstrating the environmental compatibility of the axial rotor design have been achieved, which is a critical success factor for any MHK system.

A graphic of the project execution is shown in Figure 2.1. Specific project accomplishments related to the goals and objectives of the project are also discussed below.

Figure 2.1 Execution of Verdant Power “Improved Structure and Fabrication of Large, High-Power KHPS Rotors” Project

2.1 Design an Improved Blade Structure for Larger, Higher-Power Rotors

Original Goal and Objective:

The goal of this task is to review the design basis of a 5m axial rotor to develop an improved blade structure for larger, higher-power rotors necessary for progression to a commercial KHPS product. The original design premise will achieve:

- an increase in structural integrity by modeling and then static and fatigue testing, suitable for scale-up; and
- an evaluation of cost-effective manufacture that enhanced the commercial scalability.

Other factors considered included enhancing certifiability and maintaining rotor performance for both power and environmental compatibility.

Accomplishments:

This effort, advanced by Verdant working with partners from the University of Minnesota (UMN), Sandia National Labs (SNL), and the National Energy Renewable Laboratory (NREL), was accomplished over the 2008-10 time period and was based on using the significant Acoustic Doppler Current Profiler (ADCP) and KHPS (Gen 4) operational data previously generated by Verdant at its RITE Project (2006-08) as a basis for updating existing NREL wind codes¹ for use in an MHK design evaluation. The design of an improved blade structure was accomplished with considerations for:

- Evaluation and modifications of parametric models of the blade and hub, beginning with the existing Gen4c RITE design evaluated in the existing FAST code for wind blades, then adapted for water conditions
- Design requirements for 5m in-water testing were established to prepare for tasks later in the project for logistics and permitting requirements for the IWT
- Design Structural Requirements were established for 5, 7 and 10m-class scale-up rotors, which represent a range of potential operating conditions for the Verdant KHPS.

The results of this effort indicated that while relatively good agreement was seen between the RITE site data and the modified FAST predictions, the inherent limitations of the ADCP data remained a concern with regard to accurately characterizing the turbulent inflow for the design codes. In particular, to ensure accurate turbulence measurements, the need to collect high-speed, small volume measurements of the tidal flow was identified. Specifically, Acoustic Doppler Velocimeter (ADV) instruments were needed to make such measurements. These measurements were considered to be essential to validating existing models of turbulence used for loads predictions, to provide high fidelity inflow conditions for CFD model development, and to advance resource assessment of high-energy tidal flows needed for the FAST model. Therefore an additional task effort was initiated as reported on in Section 2.2.

2.2 Analyze the Rotor Blades and Hub

Original Goal and Objective:

Based on the design requirements outlined above, Verdant will develop an alternative approach for blade structures for larger, higher-power blades, with considerations of materials and fabrication methods. Both blade and hub will be analyzed for hydrodynamics and as part of the entire system. The analysis will include both CFD flow analysis and FEA load and model analysis, conducted in conjunction with Verdant partners.

Accomplishments:

This effort was a design iteration cycle conducted over the 2009-11 timeframe as advanced by Verdant working with its partners from UMN and SNL, with additional assistance from the University of California, Davis (UCD), to complete the objectives. As an additional effort, Verdant, working with the Oak Ridge National Laboratory (ORNL), conducted in-situ turbulence measurements to better inform the modeling. The analysis of the rotor blades and hub included the following:

¹ Please see Section V for a description of these codes.

- Computational methods to analyze the performance, load and flow characteristics of the Verdant Gen5b KHPS turbine were conducted by SNL, working with UCD. Both CFD and blade element and momentum (BEM) tools were to be used for the design and analysis, providing performance characteristics for both 'clean' and 'dirty' (biofouled) blades consistent with other models.
- An FEA of the Gen5b rotor blade was conducted by SNL to verify the blade design. The model was used to predict modal frequencies and shapes, strain fields, buckling loads, composite failure under extreme loading conditions, and fatigue damage anticipated for a 20-year operational life. The results indicated that the buckling and fatigue analyses showed a large margin of safety for this blade design.
- The UMN St. Anthony Falls Laboratory (SAFL) conducted high-resolution Large-Eddy Simulation (LES) computational model development to study the 3D wake effect of the turbine, and significantly advanced the understanding of wake phenomenon for this open-bladed turbine design.
- Alternatives were evaluated for the root mounting of the rotor, with threaded inserts and T-bolts having the best structural performance. In addition, the threaded insert design was simpler and had lower short-term cost, so this blade was chosen for the final prototype design.
- Verdant designed and installed in-water mounts for ADV instrumentation provided by ORNL to make detailed hub-height turbulence intensity (TI) measurements. These indicated that the initial TI estimates used for the rotor design² were valid.

The analysis methods and results conducted during this project advance the application and understanding of previously-developed codes as adapted for use in MHK axial blade applications, leading to design and analysis needed for full-scale in-water testing and achieving TRL 7/8.

2.3 Complete Design for Manufacture and Fabricate the Rotor

Original Goal and Objective:

As part of the iterative design process, Verdant will coordinate with partners to ensure that the final rotor design is readily manufactured in low volume yet suitable for high-volume production. Additionally Verdant shall perform fabricator selection based on suitability, quality control, and cost, and fabricate the rotor (and hub) according to a Quality Management System (QMS) for lab and in-water testing.

Accomplishments:

Verdant, working with partner Manufacturing Resources, Inc. (MRI), evaluated and selected Energetx Composites (Holland, MI) to act as the composite rotor blade manufacturer under an evolving QMS production standard. As part of the iterative design process, Verdant, MRI and Energetx evaluated the design for manufacture factors, resulting in process modifications that enabled and advanced manufacturability.

² Please see ORNL/VP technical poster - REF [9]

Specifically:

- Manufacturing design was reviewed by Verdant, MRI and NREL-subcontractor Wetzel Engineering.
- Pre-qualification of four composite manufacturers and indicative quotes from manufacturers were solicited and Energetx was selected.
- Initial production PO was issued by Verdant to Energetx.
- First Article Inspections (FAI) under an evolving Verdant QMS were conducted in July 2011, revealing some manufacturing issues, which were resolved with a follow-up prototype production run in September 2011.
- A sample prototype blade for lab testing was shipped to NREL in November 2011. After NREL static and fatigue testing was completed, the set of blades for in-water testing was cleared for use in May 2012.
- Follow-up production methods were explored with Energetx to allow for manufacturing improvements for the Gen5 production blades, under a QMS continuous improvement control process.

Through this iterative design manufacturing and fabrication effort, Verdant Power has achieved an improved blade structure that can be manufactured at the 5m scale with indications of cost-effective manufacture at higher volumes. Similarly, the costs for scale-up to the 7m and 10m class composite blade are also at an indicative cost-effective level for production targets. Working with a US-based composite manufacture partner has enhanced the deliverability of a production blade at the initial 5m scale for production and is on target for larger-scale blades.

2.4 Conduct Testing of the Rotor (Static and Fatigue) in the Lab

Original Goal and Objective:

Full-scale static testing of the blade, in accordance with established wind turbine blade protocols will be accomplished. Additionally, an accelerated fatigue testing protocol will be performed on the blade that is based on load variation requirements for the kinetic hydropower blade as defined in the design requirements document.

Accomplishments:

In conjunction with NREL, static and fatigue testing of the fabricated composite blades was accomplished during September 2011 - April 2012 at its testing facility in Boulder, CO. This effort included:

- Static and fatigue test setup and protocol establishment with NREL.
- The primary objective of the test was to apply flap-wise loads simulating the 20-year lifetime damage equivalent loading to gain confidence in the structural integrity of the blade prior to the IWT.
- The test load spectrum included periodic quasi-static load blocks to simulate extreme loads and to detect any structural changes. The load matrix was executed according to the test plan.
- Following the fatigue load cases, a factored extreme static load of 200% was applied to the blade in the flap-wise direction.
- The blade endured each of the load cases without permanent changes in shape or structure. The blade stiffness was not observed to decrease during the test.

Local or global plastic deformations were not observed during the test, indicating a successful structural result.

The execution of the static and fatigue testing by the independent NREL lab has accomplished all objectives of the effort, including confirmation of the structural performance of the 5 m blade for design life usage of 20 years.

2.5 Conduct an In-Water Test (IWT) at Full Scale

Original Goal and Objective:

An in-water test of the full-scale rotor design will be conducted at either a DOE test center or at the Verdant Power RITE Project site. While the original 2007 proposal suggested that perhaps some other DOE test centers would be available, in the end accomplishment of all objectives was only possible due to the availability of the fully-permitted RITE site, and associated facilities and equipment.

Accomplishments:

In-water testing of the (Gen5) composite-blade KHPS rotor was accomplished during August - September 2012 at the RITE Project site, located in the East Channel of the East River (New York, NY). In order to conduct the test, the updated rotor was installed on a Verdant Power dynamometry (Dyno) turbine equipped with monitoring instrumentation. Specifically:

- Pre-planning for the execution of the IWT was conducted beginning in 2010 and included a detailed schedule for IWT Dyno turbine refurbishment and logistics for composite-blade rotor integration, including all engineering, fabrication, assembly, and testing at a Verdant Power-leased shop site in Bayonne, NJ.
- Major Dyno turbine component refurbishment began in 2011 along with a new Data Acquisition System (DynoDACS), and design and fabrication of new Dyno turbine components specific to the IWT.
- Dyno turbine re-assembly began in January 2012, and the unit was substantially assembled and tested in July 2012.
- All resource logistics were executed, including receipt of permits from the New York State Department of Environmental Conservation (NYSDEC) and US Army Corps of Engineers (USACE), ADCP instrumentation installation (August 2012), and readying of environmental instrumentation (Dual-Frequency Identification Sonar (DIDSON)).
- All transportation and on-water work to execute the IWT was conducted during August 14 - September 13, 2012 according to Verdant's logistic plan.
- Actual in-water dynamometry testing was executed per a planned testing protocol during August 29 - September 11, 2012.
- Removal/inspection of the Dyno turbine was completed on September 13, 2012
- Post-processing of data from the IWT has been accomplished and is reported on in this report.

The execution of the IWT, and subsequent data post-processing, was a significant undertaking and completed the accomplishment of all objectives of the contract, including verification of the performance of the blade in actual full-scale (TRL 7/8) conditions (albeit for a short time period) (See Figure 2.5.1). The post-processing of

dynamometry data confirmed the structural performance of the 5m blade design. Preliminary analysis indicates technical and manufacturing feasibility for scale-up and for design life usage under 5, 7 and 10 m-class expected operating conditions.

Figure 2.5.1 IWT Dynamometry Turbine Deployed at RITE (August 2012)

3. Summary of Project Activities

The execution of the project was organized by a series of ten tasks with the objectives to: (1) design; (2) analyze; (3) develop for manufacture and fabricate; and thoroughly test, (4) in the lab and (5) at full scale in the water, an improved KHPS rotor blade. This new blade was designed to allow KHPS rotors to be stronger, more long-lived, and more cost-effective and to operate turbines in larger sizes and at higher power levels.

All project activities were performed and results achieved, significantly advancing the original hypotheses over the course of the project. In general, there was only limited departure from the planned approaches and methodologies, however, as detailed below, an augmentation was required in terms of real-world water velocity measurements to significantly advance the accuracy of the inflow conditions (particularly turbulence) to the blade and turbine design and analysis computer codes used by the MHK industry. As expected, there were also some improvements required in the blade fabrication process under a QMS approach to first article manufacture.

As described below, the lab and in-water testing activities were a complete success, with project results are summarized below.

3.1 Task 1 - Perform CFD and Load Derivation on Blade/Rotor Systems

At the initiation of the project in 2008, Verdant Power developed a Power Spectral Density (PSD) characterization of inflow at the East River in New York, NY. The PSD for MHK is significantly different from the PSD for wind. Loads calculations based on the PSD of wind, and incorporated into the FAST dynamic code, did not match data from Verdant's East River measurements (taken during the Gen4 turbine tests at RITE - 2007). Therefore, working with NREL, a refinement to the turbulence model with correlated loads was developed³.

Supporting this effort, researchers at the University of California, Davis (UCD) completed URANS simulations of the Gen5a rotor using Overflow 2, a NASA-developed and validated code. These simulations were used to predict loads, performance and flow characteristics for the nominal design condition, water velocity (U) = 2.5 m/s, rotor diameter (D) = 5 m, and rotational speed (N) = 36 rpm.

CFD results were compared with Verdant's WT_Perf blade-element model (BEM) predictions and FAST simulations, with good agreement seen in the predicted rotor power between the models at the design speed. Table 3.1.1 shows the summary data at 2.0 m/s, normalized to the actual IWT rotor test results.

*Table 3.1.1 Gen5b Rotor Performance Summary
(Normalized to IWT Water Speed – 2.0 m/s)*

	Rotor Power (kW)	Torque (kN-m)	Method (40 rpm)
UCD	1.05	1.19	Overflow, 9x
	1.19	1.34	WT_Perf - Clean
	1.14	1.27	WT_Perf - Dirty
UMN SAFL	0.53	0.66	LES Grid III
Verdant Power	1.06	1.18	FAST
	1.09	1.23	WT_Perf
Verdant Power In-Water Test	1.0	1.0	5m RITE In-Water Test (Flood @ 45 rpm)

³ Please see Section 5 for details of the NREL codes.

Characteristics of the mean flow around the Gen5a rotor were also examined by UCD, an example of which is shown in Figure 3.1.1.

*Figure 3.1.1 Wake Vorticity and Surface Flow Visualization for Gen5a Rotor
($U = 2.5$ m/s, $N = 36$ rpm, $D = 5$ m)*

3.2 Task 2 - Determine Design Requirements

The design of the new blade for larger and higher-power applications was targeted at the market and site conditions for MHK systems.

MHK Market and Site Criteria

In determining a range of applications for a larger rotor for higher-power turbines, Verdant utilized recent resource assessment and market studies to assess and develop the design requirements for the rotor. This analysis focused on the US and worldwide market opportunities and reflected the rotor and turbine sizes most likely to have significant markets in the next three to ten years.

Emphasis was placed on opportunities evolving both in the tidal and river MHK markets, which offer two unique opportunities. Worldwide, tidal resource opportunities are being advanced by the US (in New York, Maine and Puget Sound), the UK (at sites in Pentland Firth and others under consideration by the Crown Estate), and in Canada (particularly the Bay of Fundy and Nova Scotia). Various river resource opportunities (unidirectional flows) are also being explored, especially since rivers can provide high capacity factors that make these sites even more economically favorable. Another driver in the design requirement development is the opportunities for economic incentives to support a developing MHK industry, including feed-in tariffs and initial development grant funding. The combination of these factors, coupled with an understanding of the water resources, resulted in design requirement scenarios as follows:

- 5m class - tidal operation at 56kW with peak water velocity of 2.5 m/s (representative of the RITE Project site where depths are limited and the new rotor will be tested).
- 7m class - river operation at 110kW with peak (unidirectional) water velocity of 2.5 m/s (representative of potential shallower riverine conditions worldwide).

- 10m class - river operation at 110kW with peak (unidirectional) water velocities of 2.0 m/s (representative of larger, shallow riverine environments).
- 10m class - tidal operation at nominal 500kW with peak tidal water velocities of 3.3 m/s (representative of developing large commercial tidal arrays in the Bay of Fundy, Canada; and Pentland Firth, UK).

This range of size classes and representative site conditions brackets the developing market for MHK systems under consideration by Verdant Power.

3.2.1 Determine Parameters for In-Water Testing

During 2007-08, Verdant completed the inspection and analysis of its RITE Project Gen4 turbines, including the dynamometer turbine (T1). It was determined that this unit could be used to support the IWT. Though requiring some significant refurbishments, this re-usage would still provide significant value and cost-savings to the AWPP project. Preliminary and final plans were drawn up for equipment refurbishment and replacement of T1 components as necessary for its re-use for the in-water testing of the prototype rotor (see Figure 3.2.1.1).

Figure 3.2.1.1 The Gen5 Rotor shown attached to the existing dynamometer turbine (prior to fairings) for the In-Water Test (IWT)

The essential parameters for conducting the IWT were determined to be:

- Conduct the testing at the existing RITE site – a site with well-documented water velocity and bathymetry, and existing shoreline infrastructure and Control Room (used by Verdant for 10 previous deployments).
- Modify the existing RITE environmental permits for the IWT and comply with all applicable permit terms.
- Deploy dual ADCPs in the channel for upstream and downstream water velocity data.
- Utilize the existing (refurbished) Dyno turbine to conduct the IWT, providing significant cost savings to the project.
- Retrofit a special IWT hub, equipped with the new composite blades, to the existing Dyno turbine shaft.
- Assemble, test and deploy the Dyno turbine.

- Conduct the two-week IWT and data acquisition through an improved DynoDACS and blade load strain gage system.
- Retrieve and secure the Dyno turbine.

This sequence of activities took place during 2011-12 as discussed below.

3.2.2 Determine Structural Parameters for In-Water Testing

The load distributions derived from the Task 1 activities were used to provide the structural requirements analysis of the blade and hub. Verdant coordinated the project partners to determine a consensus load profile for each operating condition.

The resulting final design parameters for prototype fabrication and testing is described in Table 3.3.1 below.

3.3 Task 3 - Detailed Structural Design Alternatives (Iterative with Task 4)

Based on the CFD and load derivation studies conducted in Task 1, the rotor structural design parameters, and in-water testing protocols identified in Task 2, Verdant, in conjunction with MRI, completed a study of structural design alternatives, including considerations for the material selection and the concomitant fabrication techniques and methods.

The criteria for the designs included strength, fatigue resistance, corrosion resistance and short-term and potential long-term manufacturing costs. Considerations included several blade structure arrangements as shown in Fig 3.3.1, and root mounting approaches as shown in Fig 3.3.2.

Figure 3.3.1 Alternative Axial Rotor Concepts

a) an AlMag blade with a through-bolted hub, similar to the Verdant Gen4c blade; b) a composite fiberglass blade with blade-axial bolts; and c) a flat-mounted clamped or through-bolted fiberglass blade. The concepts were evaluated on the basis of cost and structural performance at both 5 and 10m-class bases.

Figure 3.3.2 Alternative Blade Root Mounting Concepts

Solid models were made of the candidate designs, and each approach was analyzed for structural properties and production costs for four target class and market sizes: 5m, 7m, 10m-river and 10m-tidal. Of these, the threaded inserts and T-bolts had the best structural performance in terms of required weight and hub diameter. The root mounting with the bonded threaded inserts had the lowest cost, so this blade version was chosen for the final design to accommodate the range of scale-up for commercial turbine rotors.

The resulting blade design was based on fiberglass (e-glass), within a vinyl ester (or epoxy) resin for the high-pressure and low-pressure skins and shear web, methacrylate bonded skins and round heavy root section. The void volumes within the blade would be filled with a syntactic resin bubble mixture to ensure water displacement to maintain balance over a long operational life. The balance of the rotor would be a cast ductile iron hub fairing, and tailcone as described in Task 4.

Table 3.3.1 Gen5b Rotor Blade Parameters

Structural Parameter	Values for 5m Rotor Blades
Flow	2.5 m/s with initial inflow PSD
Materials	E-glass fibers in vinyl ester resin, methacrylate adhesive, stainless steel root stud inserts
Loadings	Based on FAST code runs and structural calculations of blade materials and elements
Testing	Static (10 kNm edge, 53 kNm flap) acceptance testing at manufacturer prior to lab testing

3.4 Task 4 - Hydrodynamic Blade Design (Iterative with Task 3)

This task focused on the development of specific blade shape designs utilizing specific foil shapes, distributions and thickness tapers that simultaneously met the structural and hydrodynamic performance criteria, while being cost-effective and consistently manufacturable.

To accomplish this, Verdant partnered with SNL and UCD to evaluate various airfoil shapes developed by the National Advisory Committee for Aeronautics (NACA) based on the criteria for cavitation avoidance and lift insensitivity to surface soiling (due to biofouling).

The alternative blades have been designed using the NREL HarpOPT code. This code is based on WT_Perf but also includes cavitation effects. Several foils were utilized and the differences in energy capture as modeled were shown to be small.

The results of this work concluded that the NACA 44XX Series (as was used in Verdant's prior KHPS turbines) continues to provide an excellent balance of the design criteria required. Thus the NACA 44XX foil family was chosen for the final design. Based on this airfoil survey and iterative with the structural alternative requirements discussed in Task 3, four final concepts were designed for further consideration as shown below.

Table 3.4.1 Composite Blade Design Characteristics

Rotor Diameter - Resource	5m - Tidal	7m - River	10m - River	10m - Tidal
Generator Class	56 kW	110 kW	110 kW	500 kW
Peak Water Velocity	2.5 m/s	2.5 m/s	2.0 m/s	3.3 m/s
RPM	40 rpm	31 rpm	22 rpm	31 rpm
Root - Thickness/Twist	Proprietary Verdant Power Design Values			
Tip - Thickness/Twist	Proprietary Verdant Power Design Values			

Working with MRI, the larger, higher-power rotor shapes were preliminarily reviewed with potential composite blade suppliers for manufacturability at low initial volume as well as at scaled-up volumes.

Critical to achieving cost-effective blade manufacture is a feasible and repeatable manufacturing process that is optimized for the blade design and performance requirements. Through close collaboration with the blade supplier, Energetx, the production tooling, work methods, and in-process quality checks were designed to limit costs and ensure a functional quality control system.

Successful, cost-effective, scale-up to larger blade sizes is based on leveraging the lessons learned from the design, testing and production optimization of smaller blades, and capitalizing on the blade supplier's broader experience with the most advanced composite materials and processes. Through this first-run project these initial processes were first implemented for low-volume runs of the new composite blades at the 5m size.

3.5 Task 5 - Hub Design (Iterative with and following Tasks 3 and 4)

This task was to develop a hub design suited to the above blade design in terms of structure and materials, and also to the balance of the turbine, including drive train. Considerations for the fabrication of the hub were also included.

3.5.1 Gen5 Hub Design

The Gen5 hub has been designed to achieve multiple objectives of low cost, durability, corrosion resistance, long life, rotor performance, and ease of assembly and disassembly. The completed design is shown in Figure 3.5.1.1. The material is ductile cast iron, which has been used successfully for many wind turbine rotor hubs. The connection to the Gen5 turbine shaft is a tapered connection. This simplifies the assembly, and helps to keep the size of the rotor hub small, reducing weight and increasing hydrodynamic performance of the rotor. Copper-based alloys were also investigated for this application. Functionally, they are suitable, but are about 3 times as expensive. With appropriate coating and protection by zinc anodes, corrosion of the ductile iron should be reduced to acceptable rates.

Figure 3.5.1.1 Final Gen5 Hub Design

3.5.2 Hub for IWT Dynamometer

In order to conduct the IWT dynamometry and load testing, a one-off dynamometry hub was designed that could accommodate the new rotor design and be retrofitted to the Dyno turbine (Gen4 KHPS-type straight shaft). This hub has the same blade mounting geometry as the Gen5 hub but is fabricated of high-strength steel rather than the cast iron of the Gen5 hub. It was also designed to accommodate strain gage sensors for the IWT load measurements. The IWT test hub was quoted, and ultimately fabricated, by Leiss Tool and Die in Somerset, PA.

3.6 Task 6 - Conduct Blade, Hub and Turbine Analysis

As part of this task, three separate computational analyses were conducted to evaluate the rotor (blade and hub) design. Additionally, an evaluation of Turbulence Intensity (TI) was conducted to provide the required inflow information for the other analyses.

3.6.1 FEA Hub & Blade Analysis

An FEA of the Verdant Power Gen5b rotor blade was conducted by SNL to verify the calculations on which the blade was designed. The FEA model was used to predict

modal frequencies and shapes; strain fields, buckling loads, and composite failure under extreme loading conditions; and fatigue damage anticipated for a 20-year operational life. The results indicated good margins of safety for buckling and fatigue for this blade design.

3.6.2 Hub & Blade Design CFD

Additional computational work was done by UCD for SNL. These computational methods were used to analyze the performance, load and flow characteristics of the proprietary Verdant Gen5b KHPS turbine. Both CFD and BEM tools were used for the analysis and results from the two computational methodologies will be compared to each other. Two water flow conditions were analyzed in this study -- 2.0 and 2.5 m/s. The Verdant Gen5b turbine operates at a fixed 0° pitch and constant 40 RPM. At each operating condition, CFD was used to compute the rotor power output, spanwise load distributions, surface pressure distributions, surface flow patterns and wake vortex structures. BEM was used to compute rotor power and spanwise load distributions. The conclusions from the study indicated consistent results from all computational methods as shown in the table below.

Table 3.6.2.1 Model Predictions of Composite Blade Rotor Power

Computational Tool	Water Velocity = 2.0 m/s	Water Velocity = 2.5 m/s
Overflow (UCD)	31.6 kW	61.5 kW
HARP-Opt (UCD)	34.1 kW (35.7 kW - clean*)	65.5 kW (68.9 - clean*)
WT_Perf (NREL)	32.7 kW	63.4 kW
FAST (NREL)	31.8 kW	60.5 kW

* clean refers to a non-biofouled rotor condition

Surface flow patterns indicated significant amounts of cross flow and separated flow over the inner one-third of the blade. There is trailing edge separation along the entire span of the blade at 2.0 m/s and 2.5 m/s. Surface pressure distributions show the flow transitioning between 30-50% of chord for a clean foil. Transition was fixed at 10% of chord for a soiled foil. The degraded rotor performance is probably a combined result of early flow transition, massive separation inboard and trailing edge separation along the blade length.

3.6.3 Hi-Resolution Wake Analysis

Using the model developed in Task 1, the UMN SAFL model was updated to the new Gen5b rotor (blade and hub) design, and extended to include the balance of the turbine structure. This analysis derived general wakes for the water velocities in the design document. The model characterized the 3D wake effect of the turbine and significantly advanced the understanding of wake phenomenon.

3.6.4 Turbulence Intensity Evaluation – ADCPs and ADVs

As discussed in Task 1, NREL provided a new turbulence simulation code to model the PSD that was measured by Verdant. The inflow data created by the turbulence simulation code was used in a FAST simulation. The FAST model had good agreement with the data from the Gen4 turbines that operated the East River during 2006-08;

however, the inflow turbulence was based on an untested approximation from ADCP data.

It was decided that additional refinement and confirmation of the accuracy of the inflow turbulence through Acoustic Doppler Velocimeter (ADV) measurements would be important to the project and ongoing MHK turbine rotor design. The existing mounting piles at RITE would further allow for measurements to be taken at hub height. This work was supported with ADV equipment and other technical support provided by Oak Ridge National Laboratory (ORNL), which allowed this previously unplanned field data collection to proceed.

Field Data Collection:

Verdant received the required permit modification from NYSDEC and USACE for installation of the ADVs in the RITE Project site. This instrumentation, as shown in Figure 3.6.4.1 was installed in the river during the week of June 6, 2011. Data was collected in conjunction with the deployment of two ADCPs for a period of 56 days.

ADV Data Analysis:

Analysis of the ADCP/ADV data was performed, and it was concluded that Verdant's estimated TI of 20% for the RITE Gen5 KHPS design basis was a reasonably-conservative estimate for $V_w > 1.5$ m/s at the RITE site. A more detailed turbulence profile and PSD was developed and will subsequently be used for the inflow for Turbsim and the FAST model. A joint ORNL/VP paper was delivered on this subject (REF [9]).

Figure 3.6.4.1 ADCP and ADV Instrumentation Deployed at RITE (June 2011)

3.7 Task 7 - Design for Manufacture

The blade and hub designs were completed as described in tasks 3, 4, 5 and 6. Verdant Power, through its production QMS, and working with MRI, prequalified potential vendors and solicited quotes from four US manufacturers, with a concentration on establishing estimated initial costs for non-recurring engineering/tooling and low-volume production costs, as well as for considerations for future higher-volume and larger-scale production costs.

Energetx Composites (Holland, MI) was selected as the Gen5 blade supplier, based on its long-term experience with fiberglass production, high quality, history with boat building, recent large wind turbine blade production, cost, and proposed approach to building this blade. Throughout the consultative process, Energetx was directly involved in developing solutions to detailed blade manufacturing issues.

The final fiberglass, resin and syntactic foam materials were selected and the lamination, bonding and filling manufacturing process steps were finalized for the resin infusion of the high- and low-pressure skins and the shear web; the bonding of the shear web and the skins to each other; and the bonding of the threaded root inserts.

Various materials for the bonded root inserts were considered including nickel aluminum bronze, but 316 stainless steel was selected as the best balance of strength, longevity and cost. Energetx performed insert pull-out tests, which were successful. Nonetheless, it was identified that the inserts were a major factor in the blade fabrication issues, and, depending on equipment costs, a different fastener arrangement may allow additional future improvements to the root molding process.

3.8 Task 8 - Fabricate Prototype

As outlined above in the previous task, Design for Manufacture, the scope of this task was for Verdant, working with its production quality manager MRI, to perform a fabricator selection process to choose the blade and hub fabricators, based on the key factors of suitability, quality control and cost. The fabrication process was then to be closely monitored and evaluated, and final acceptance performed for the rotor components to be released for testing, at the NREL lab and in-water at RITE.

All activities under this task were accomplished during the course of the project, and included:

- A rotor blade fabricator selection process and fabrication by Energetx Composites conducted from February 2011 - June 2012 (Figure 3.8.1.1).
- An IWT hub fabricator selection process and fabrication by Leiss Tool and Die, conducted from October 2011 - May 2012.

Throughout the fabrication process, the application of quality management practices for first-time manufacturing was an iterative process control. Quality checks under First Article Inspections (FAI) witnessed by Verdant was an important element and continuous feedback between the design and manufacturer yielded confidence in the

improved blade structure that can be manufactured at the 5m scale, with indications of cost-effective manufacture at higher volumes and large scales. Similarly, the indicative timeframes for supply chain delivery for multiple KHPS composite blades was established, providing the basis for production targets.

3.8.1 Fabricate Composite Rotor

The genesis of this project was the awareness that the fabrication of the composite blade is critical to the success of developing a larger, higher-power KHPS. The establishment of a relationship with a qualified and capable composite manufacturer was essential to accomplishing the iterative QMS for fabrication and to assess low-volume production leading to higher-volume production.

Working with production QMS partner MRI, Energetx Composites was selected after pre-qualifications and indicative design quotations from four composite manufacturers. The rotor fabrication proceeded as follows.

Blade Fabrication Tooling

Verdant issued a purchase order to Energetx for the blade fabrication tooling work. A blade plug for each skin (high pressure and low pressure) was cut on a computer numerical-controlled milling machine from the computer-based 3D blade model files. The female blade molds were formed around these plugs and used for molding the actual FRP bladeskins.

Tooling and jigs were also created to form and locate the cavities for the root inserts and for molding, assembly and blade measurement.

First Article Inspection (FAI)

The first blade was produced and tested during the week of July 18, 2011, attended by Verdant Power personnel under an FAI proprietary QMS. The quality of this blade was considered generally good; however, there were a few fabrication issues that required correction, including misalignment that led to difficulties in bonding the root inserts and a slight blade distortion that was likely due to shrinkage caused by the application of the resin/bubble mixture filler.

Figure 3.8.1.1 5m Composite Rotor as Fabricated for the RITE Project

The static test of the first blade was also conducted and overseen by Verdant personnel. The blade performed very well under both edge and flapwise testing with no structural damage indicated. Specifically, the applied flap loads far exceeded the design loads (~1.7x) with excellent structural performance. The blade was instrumented with 16 strain gages to measure both flap and edge strains, as shown in Figure 3.8.1.2 below. A static blade test report from Energetx was created as per the proprietary Verdant Production QMS.

Figure 3.8.1.2 Fully-instrumented Gen5b blade during static flap test at Energetx facility

Additionally, after the first item blade was tested for static strength at Energetx, it was sectioned for inspection. The sections showed several issues related to fabrication techniques, which have been the subject of ongoing improvement. These issues included voids between the internal blade elements and skins, voids in the resin/bubble fill material, and shrinkage cracks in the fill material. No material or bonding failures were observed.

A report of the testing and blade post-mortem was prepared by Energetx and an accompanying report was executed by Verdant personnel who attended the testing. Subsequent blades and portions were fabricated and inspected to improve the methodologies.

Second Inspection and Release for Lab Testing

In September 2011, Verdant Power personnel attended the flap and edge vendor static testing of the three blades prior to finishing. These tests were passed without qualification and documented as per the Verdant Power Production Quality Management plan. However, as a result of the fabrication issues previously revealed, it was decided to expand the initial static tests at NREL (on blade VP005) to include

enough fatigue cycles to ensure that the blade fatigue from the limited two-week IWT on blades VP006-VP008 would not be a risk, and that the fatigue testing be completed prior to the release of the blade for use in the IWT. This test protocol modification was performed and the blades were ultimately cleared for use in the IWT in April 2012.

Throughout the process, iterative QMS reviews resulted in improvements to the fabrication of the composite blades, which were delivered on time and ultimately successfully tested both in the lab and in the water.

Outside Testing: University of Maine

Lap shear tests on the composite materials were independently conducted at the University of Maine (UMaine) based on test coupons produced by Energetx and sent to UMaine for saltwater conditioning in preparation for the testing. A round of lap shear tests was performed at UMaine and was successful, with the 8 conditioned samples testing at an average of 949 psi, meeting the requirement.

Additionally, Energetx completed a root insert test component coupon fabrication and the UMaine bonding pullout testing on 12 inserts was successful. Pullout loads averaged over 6 times the required 45kN force, with the lowest sample pullout at 5 times the required load.

Both of these tests informed the structural integrity of the composite blade design.

3.8.2 Fabricate IWT Hub

Leiss Tool and Die (Somerset, PA) was selected as the supplier of the special IWT hub. The hub was manufactured and, through a series of iterative QMS reviews, resulted in an acceptable IWT hub that was delivered on time and approved for use in the IWT. In May 2012, the hub was shipped to HiTec Sensor Solutions (Littleton, MA) to be fitted with the strain gages that would measure blade loads during the IWT. Each blade mounting arm was fitted with two opposing pairs of strain gages in half-bridges to sense loads in the axial (flap) and circumferential (edge) directions. During rotor assembly, these strain gages were calibrated to provide rotor load information during the IWT. Figure 3.8.2.1 shows the instrumented hub in the HiTec shop prior to waterproof coating and cover plate installation.

Figure 3.8.2.1 IWT Hub Instrumented with Strain Gages

3.9 Conduct Test Stand Static and Fatigue Testing

This task accomplished full-scale static testing of the Gen5b blade, under a proprietary testing protocol established by NREL and Verdant Power.

A test protocol and matrix was developed by NREL and Verdant Power based on the loads characteristic of the water resource at RITE, provided by Verdant, and the blade design loads from the FAST model. It included several quasi-static test loads at peak load magnitudes before and after 2 million tidal simulation fatigue cycles for a damage equivalent load equivalent to the 20-year life.

Table 3.9.1 IWT Blade Loading

Relevant to IWT	Static Loads	Fatigue Cycles
Extreme Model Load	38 kNm	440,000
NREL Testing	Simulations ranging from 7-35 kNm and up to 52 kNm	2M cycle for damage equivalent

With appropriate factors and adjustments for the test equipment applied, static and fatigue load blocks were applied, totaling two-million cycles. The fatigue loads were applied sinusoidally in blocks. Quasi-static loads at higher levels were applied up to a peak root moment of 52 kNm in order to match the maximum test static moment at the blade root. The static loads were applied as periodic ramps.

During the IWT, the rotor blades were to be subjected to a test program involving up to 10 days of approximately four tide cycles per day. Relevant to fatigue, the rotors would rotate at an average of approximately 40 rpm for about three-fourths of the time, and thus each blade was to undergo approximately 440,000 loading cycles. Thus, the fatigue loadings during the IWT represent a fraction of the total 2M cycle NREL test program.

NREL completed the testing of the test blade at the National Wind Technology Center (NWTC) lab highbay facility, according to NREL's quality and safety programs, which meet international (IEC) standards. It was mounted cantilevered to the test stand using a specific adapter plate made for the blade.

In addition to testing the sample blade generally, a specific objective of the test was to apply static and a representative fatigue spectrum of loads in order to gain confidence in the suitability of the first test set of three blades for the IWT. All of the loading was in the out-of-plane (OOP) or flap direction, which constitutes the dominant loading of the blade. The magnitudes of the fatigue cycle loads applied were varied to represent the spectrum of expected in-water loads. A servo-hydraulic control system was used to apply the loading.

Strain gages were positioned with specific attention to the root transition area, to assess whether the blade had areas of particularly high strains. The output of the sensors was recorded by NREL's data acquisition system at 100 samples per second. This data included:

- Load applied (10k lb load cell)
- Blade Displacement (LVDT)
- Strains (25 strain gages)
- Blade temperature (monolithic integrated circuit type)
- Additional test data was acquired from:
 - Acoustic emission sensors – eight microphones were installed near the root transition region and could be moved during the test if acoustic hot-spots were identified.
 - Thermal imaging – a camera was used periodically to image the blade during the test, with thermographs taken of any areas showing elevated thermal signatures.
 - Video – cameras took video from two angles for the test – tip-to-root and overhead from root-to-tip.
 - Photos – digital photos were taken throughout the test program, including setup and test execution.

A basic modal (vibration) test was performed by manually exciting the blade while it was mounted to the test stand and performing an FFT on the acquired data to determine its principle flap and edge Eigen frequencies.

Figure 3.9.1 NREL Test Setup of Gen5 AWPP Composite Blade (2012)

With testing at 3 Hz (4.5 times the usual operating rate), the testing was completed in early April 2012. The blade sustained each of the load cases without permanent changes in shape or structure. The blade stiffness was not observed to decrease significantly during the test. Local or global plastic deformations were not observed during the test.

The execution of the static and fatigue testing by the NREL lab has accomplished all objectives of the contract, including verification of the 5m blade for the design life of 20 years.

3.10 Task 10 - Conduct In-Water Testing

As recognized in the project scope, the actual execution of an in-water test at full scale of a TRL 7/8 prototype, even for a short period of time, requires a significant logistical effort, which was accomplished during the project. Additionally, the IWT dynamometry testing and post-processing of results was a significant task completed as the final effort of the project.

3.10.1 Logistics for in-water Testing

The scope of the effort was initiated early in the project by determining in-water testing parameters. Then, over the course of the project, Verdant coordinated and developed specific plans, including protocols, logistics and permits for the in-water testing of the prototype rotor as retrofitted to Verdant's refurbished Gen4 Dynamometer (Dyno) turbine at the RITE Project site.

All aspects of the task of conducting in-water testing were executed beginning in 2011, once the composite blades were under testing at NREL. The effort, which led to the deployment of the rotor at RITE on August 29, 2012, included:

- 1) *Development of an IWT protocol for rotor testing*
- 2) *Acquiring of permits and associated environmental monitoring activities*
- 3) *Design of instrumentation and data acquisition systems (DynoDACS)*
- 4) *Execution of the dynamometer retrofit process, including all procurement, fabrication and testing of components, final assembly and testing*

5) *Logistics, transport and deployment and retrieval of the Dyno turbine at the RITE site*

The following table is a chronological summary of these activities, leading up to a successful in-water test (IWT).

Table 3.10.1.1 Summary of Verdant Power IWT Activities

Month	Permits and Environmental Monitoring	Instrumentation and Data Acquisition	Dynamometer Retrofit	Logistics, Transport and Deployment
Jan 2012 (and prior)	Approve RMEE-2 plan	Complete design of new DynoDACS ⁴	Major equipment orders	Prep assembly procedures
Feb 2012	File for permit modification	DynoDACS final assembly and testing	Prep assembly procedures	Final assembly procedures
Mar 2012		Control Room systems refurbishment and test	Major Dyno turbine assembly, preparation	Establish Bayonne, NJ assembly shop
Apr 2012		DynoDACS bench testing (NJ)	Prep nacelle and pylon; Inspect hub	Transport logisticsv1
May 2012	Receive NYSDEC permit	DynoDACS turbine integration and testing (NJ)	Final assembly; Dyno turbine equipment testing	Receive blades
Jun 2012		DynoDACS testing (NJ); Calibrate strain gages (NJ)	Rotor assembly; Loads calibration	Receive instrumented hub
Jul 2012	Prep RMEE-2 instrument	DynoDACS turbine testing (NJ); Initial blade strain gage calibration (NJ)	Final nacelle assembly; turbine testing	Transport logisticsv2; transport permits
Aug 2012	Prep RMEE-2 instrument; Receive USACE permit; Install ADCPs; Conduct RMEE-2 operation/monitoring	Final strain gage calibration (NJ); Launch rotor strain gage data recording; Collect DynoDACS data	Final turbine preparation	Final transport logistics; Dyno turbine deployment

The logistics for the IWT encompassed a significant 18-month effort by Verdant to achieve the task of testing the new prototype rotor pursuant to the DOE AWPP project contract.

In preparation for the actual logistics for the IWT, Verdant developed and executed several procedures:

- Dyno turbine retrofit and ancillary component drawings, assembly procedures, and testing plans;
- Logistical schedule for personnel, manpower and vendor support, reviewed and updated weekly during the period;

⁴ Dynamometer turbine data acquisition and control system (DynoDACS)

- On-water work procedures and timing specifically for the deployment and retrieval of the Dyno turbine and environmental instrumentation, and Emergency Action Plans (EAPs);
- Test protocols and log sheets for use during the two-week data collection period.

This in-house documentation provided the guidance for the execution of the procurement, assembly, shop-testing, transportation, deployment, in-water testing (Dyno and environmental), retrieval and inspection during the execution of this project.

Permitting and Related Environmental Monitoring Instrumentation

Two important aspects of the IWT were the permitting and installation of monitoring instrumentation that allowed for the test to proceed. Verdant Power has had operating permits for the RITE Project since 2005, and in February 2012 applied for and received modifications and extensions to the two permits required for the IWT - specifically NYSDEC Permit Nos. 2-6204-01510/00001 and /00002, and USACE Permit No. NAN-2003-402-EHA.

In accordance with these permits, Verdant was required to conduct a beta test of the RITE Monitoring of Environmental Effects Plan #2 (RMEE-2) - Seasonal DIDSON Observation Monitoring, which included the use of a Dual-Frequency Identification Sonar (DIDSON) unit – a multi-element sonar that provides video-like images of underwater objects for real-time observation of fish behavior near operating KHPS turbines. The specific permitted objectives of the beta test in conjunction with the IWT were to:

- 1) Confirm the location and operational viewing coverage of the stationary DIDSON; and
- 2) Investigate the cleaning and maintenance alternatives for the DIDSON equipment that may allow for extended monitoring.

This activity was undertaken under a separate contract with the New York State Energy Research and Development Authority (NYSERDA). A DIDSON-based device, referred to as the Remotely Aimed DIDSON (RAD), was successfully designed, built and deployed by Verdant during the IWT, achieving both of the beta test requirements. Further information on this activity is available in the FERC docket for the RITE Project (P-12611).

Most importantly, in readiness for the IWT, two fixed ADCPs (ADCP-N and ADCP-S) were deployed in August 2012 and cabled to shore for continuous, real-time data collection and collected data successfully throughout the entire IWT.

Dynamometer Retrofit Process (Including Procurement and Component Testing)

Beginning in February 2012, and according to the plan established above, the Dyno turbine retrofit process encompassed a sequential retrofit of major sub-assemblies with concurrent testing, calibration and verification for readiness. The table below summarizes this process.

Table 3.10.1.2 Dynamometer Retrofit Sequence – February - August 2012

Major Dyno Assembly	Execution Sequence	Test Verification and Release
4.1 Pylon/Nacelle	March - April 2012: Delivery to Bayonne, NJ assembly shop, inspection, refinishing and painting	Refurbishment completed April 2012
4.2 Bearing Housing, Brake and Torque Cell	May-June 2012: Install factory-refurbished brake and recalibrated torque cell on bearing housing assembly	Sub-assembly test completed May 2012
4.3 Hub and Rotor Assembly	June 2012: Receipt of major components and hydraulic torque wrench	Rotor assembly completed June 2012
4.4 DynoDACS	May - August 2012: Continuous testing (off-site)	Final Land Systems test at RITE Control Room August 2012
4.5 Final Dyno Assembly	July 2012: Nacelle annular ring bolt-hole misalignment diagnosed and realigned	Assembly, ready for transport August 2012
4.6 Blade Strain Gage Instrumentation and Calibration	June 2012 (HiTec rep onsite): Rotor mounted on floor stand, Flap strain gage calibration	Edge calibration, final edge blade strain gage and DACS torque calibration completed August 2012

The retrofit sequence allowed for substantial readiness for transport of the Dyno turbine as of the second week in August for installation at the RITE site the last week in August 2012. Figures 3.10.1.1 to 3.10.1.2 show stages of the Dyno assembly process.

Figure 3.10.1.1 Final Assembly, Testing and Calibration of IWT Dyno Turbine (Bayonne, NJ - July 2012)

Figure 3.10.1.2 IWT Dyno Turbine Ready for Transport (August 2012)

Logistics, Transport and Deployment of the Dyno Turbine at the RITE Project Site

The process of transporting the assembled Dyno turbine from the assembly shop to the barge loading site, the on-water deployment at RITE, and retrieval and return of the unit to storage was a significant undertaking that was successfully executed during August - September 2012. Highlights included:

- Land-based challenges related to moving the assembled Dyno turbine from the shop over a 2-mile route were resolved with significant help from the barge contractor, after consideration of several transport options. Figure 3.10.1.3 shows the Dyno turbine en route to the deployment barge.
- Under the proprietary Verdant Power Quality Management System (QMS), a detailed plan was developed and approved for the deployment and retrieval of the turbine. This included the following elements:
 - The IWT deployment sequence was set for Wednesday, August 29, 2012, after confirming readiness with weather forecasts, on-water contractor availability, US Coast Guard (USCG) notifications, emergency action plan (EAP) updates, and other permit and instrumentation readiness procedures.
 - The on-water sequence was driven by the three slack tides during which in-water installation must take place.
 - During Slack #1 (High Tide) the barge adjusted the location of north buoy and returned to Hallet's Cove.
 - Deployment was scheduled for Slack #2 (Low Tide). Prior to this, the barge arrived at the RITE site and lowered its spuds, followed by divers entering the water for final deployment preparations. The turbine was lifted from deck, lowered into the water, and placed on mounting studs by the divers. The Dyno turbine umbilical was run to shore by auxiliary boat and used to connect the DynoDACS data cable and hoses. The divers installed the yaw stop and secured the mounting washers and nuts. The divers then applied the final torques to the mounting stud nuts, but noted a discrepancy which required further review. Release for testing was placed on hold until divers were topside for debrief.
 - Concurrently, the RAD system was successfully deployed during Slack #2 from a second barge.
 - During the de-brief, divers reported that two of the mounting studs had pulled out of their threaded holes in the pile top adaptor. At the completion of Slack #2, the Dyno turbine was held in place with six of eight studs and nuts, and a review of location of the mounting plate attachment failure indicated that the measured bolt torque should be confirmed on the existing six nuts/studs during a confirmation dive on Slack #3.
 - During Slack #3, divers dove to confirm the torque on the six good nuts. Based on the results of this confirmation, the IWT protocol was modified to test only on the flood tides until a weld of the remaining two slots could be scheduled. A weld plan was confirmed for the following Tuesday, September 4, to allow both ebb and flood testing.

Figure 3.10.1.3 Dyno Turbine En Route to Deployment Barge

Conduct In-Water Test

At the conclusion of Slack #3 on August 29, 2012, the Dyno turbine was released for testing per the planned protocol. Section 3.10.2 describes the IWT testing protocol, which was executed during August 29 - September 7, 2012.

Equipment Removal

After the completion of the IWT testing phase on September 8, 2012, the plan for the turbine retrieval was executed on September 11 using an approved on-water sequence similar to the deployment sequence, though in reverse. The Dyno turbine was removed during slack tide and placed on its carrier on the barge deck. The barge returned to nearby Hallet's Cove where the turbine was inspected, and the strain gage data was offloaded. At the end of the flood tide the barge returned to the Bayonne facility for further rotor and Dyno turbine inspection and transport to storage.

The two ADCP instruments remain at the RITE Project site, continuously recording water velocity data. The RMEE-2 RAD system was removed from the site on October 11, 2012, having completed its beta testing.

*Figure 3.10.1.4 IWT Dyno Turbine/AWPP Rotor After Completion of IWT
(September 11, 2012)*

In summary, the logistical planning for a full-scale TRL 5/6 in-water test is a significant undertaking of time, personnel and expense, through a coordinated effort of permitting, planning and documented procedures.

3.10.2 Dynamometry Testing

The scope of this task was to perform dynamometry testing on the prototype rotor in order to characterize its operation and measure its performance. The testing utilized a controllable brake that was used to load the rotor at different levels from no-load (brake off) to stall at all available water velocities. The dynamometry instrumentation collected a large data set of real-time performance measures (e.g. torque, rotation rate) that was stored for post-processing and analysis. Rotor power curves and an overall operating curve were determined along with rotor efficiencies.

In-water Dynamometry Testing Methodology

The dynamometry testing was based on a protocol to be used for up to ten days of testing during the two-week IWT. The testing data was acquired from three sources:

- In-water resource instrumentation – ADCPs for water velocity (and level)

- DynoDACS system - acquiring Dyno turbine status and blade performance data
- Rotor blade strain gage instrumentation, self-contained on the rotor

The processing of the data from these three systems included adjustment of raw data to calibrated, synchronization of time stamps, time-smoothing of the data, and analysis of collected parameters to develop rotor power curves and overall operating curves along with rotor efficiencies and loads. In preparation for the actual dynamometry testing, the following methodology and instrumentation was designed and adapted in the course of the project. The specification for the dynamometry data collected was as shown in the table below.

Table 3.10.2.1 IWT Data Collection

Measured Value	Sensor Type	Symbol	Derived Value
Water Speed and Water Level	ADCPs (2) 10m Upstream and downstream of Dyno turbine	V_w	$TAW\eta = P / [\frac{1}{2}\rho A V_w^3]$
Rotor Torque	Load cell – to DynoDACS	τ	Power= $\omega\tau$
Rotor Speed	Optical encoder – to DynoDACS	ω	
Blade Flap and Edge strain	Strain gage bridge (6) in nacelle	m_x and m_y	Blade load moments

The methodology for acquiring dynamometry data was revised to one in which the brake air pressure (and thus torque) was manually set to keep the rotor within a reasonable operating speed range. The actual testing methodology used to accomplish the data acquisition is illustrated in Figure 3.10.2.1

Figure 3.10.2.1 RITE IWT Testing Methodology

Data acquisition and Processing

As noted above, three distinct data sets were acquired during the IWT.

1) Water Velocity – ADCPs

The deployment of two Acoustic Doppler Current Profilers (ADCP) to concurrently collect water velocity data upstream and downstream of the Dyno turbine was crucial to the IWT protocol. In August 2012, prior to the Dyno turbine deployment, Verdant deployed two RDI workhorse ADCPs as shown in Figure 3.10.2.2 (at North (N) and

South (S) positions relative to the Dyno turbine). These instruments collected data throughout the IWT.

Figure 3.10.2.2 IWT Site Layout Showing ADCP-N & ADCP-S Relative to Dyno Turbine

The water velocity data for both ADCP-South and ADCP-North is shown in Figure 3.10.2.3. This figure shows the tides leading up to Dyno turbine and RAD deployment and through the duration of the IWT. The general decline in peak velocities due to the waning of the full moon (on Aug. 31) can be seen, along with lowered velocities for the downstream ADCP (north on the flood, and south on the ebb) during Dyno turbine operation. Note that this representation is a significant smoothing of the actual ADCP output, as required for visual post-processing.

Figure 3.10.2.3 ADCP- N & ADCP- S Water Velocity Data Before and During the IWT

2) DynoDACS – Rotor Torque and Speed; Other Turbine Parameters

The DynoDACS was designed to continuously acquire all dynamometry and turbine-related data in real time for use in post-processing the rotor performance data. A screenshot of the IWT DynoDACS user interface is shown in Figure 3.10.2.4 below.

Figure 3.10.2.4 IWT DynoDACS (Sample Screen Shot)

The IWT DynoDACS acquired nearly 240,000 valid data points for post processing. This exceeds by over three times the amount of data acquired during the Gen4 KHPS testing (RITE 2006-08), and fully accomplished the goal of data collection.

3) Blade Loads Package – Through Onboard Rotor Strain Gages and Recorders

Verdant instrumented the IWT rotor hub with strain gages and recorders to measure the moments on the blades continuously during in-water operation. Two battery-powered Vishay P3 strain gage recorders mounted in a waterproof housing mounted on the rotor hub to read and record the two bridges (four opposed half-bridges) in each hub arm to measure flap and edge loads. The P3 units were launched on battery power, and the recorders operated for the entire period, through transport, deployment and underwater use during the IWT, and until retrieval on September 11, 2012.

The housing was opened on September 11 and data integrity was verified. All six channels (flap and edge for each blade) successfully acquired moment data on the blades for the entire IWT, for subsequent processing and analysis.

Rotor Structural Performance

As noted previously, the NREL lab testing found adequate structural integrity for the blade for static loads exceeding the expected maximum loads, and for fatigue loads equivalent to the 20-year design life.

Accordingly, after the execution of the two-week IWT (August 29 - September 7, 2012) there was no apparent performance degradation, and upon retrieval and inspection, all the blades and the rotor as a whole looked like new (see Figure 3.10.1.4).

The lab and in-water test results for the AWPP rotor blade at the 5m diameter scale, coupled with a preliminary analysis of a scale-up, indicate that this basic structural design will be capable of being successfully scaled up to the 7m and 10m diameter classes, and to the higher powers in available flows, in accordance with the Design Parameters outlined in Task 2. As this was the design objective for commercial viability, the effort for stronger, long-lived and more cost-effective rotors for larger sizes and higher-power turbines was achieved.

Rotor Hydrodynamic Performance, Including Rotor Operating Characteristics

The processing of the recorded dynamometry data to determine rotor performance is a multi-step process, factoring in the water speed from the upstream of the two ADCPs and the rotor speed and torque from the Dyno Turbine. The DynoDACS data, acquired from the Dyno turbine, was post-processed, including being down-selected for time, torque and rotor speed; synchronized; and appropriately smoothed. Figure 3.10.2.5 shows the rotor in operation, with power (black line) and both ADCP water speed measurements for a complete ebb tide of dynamometry testing. As this was an ebb tide, the ADCP-S measured water speed (blue) was lowered relative to ADCP-N (green) due to the wake of the turbine. It can be seen that the ADCP measurements are virtually identical before the beginning, and after the end of power extraction by the rotor on the Dyno turbine.

Figure 3.10.2.5 AWPP Gen5 Composite Blade Rotor Power

From the IWT data, the Gen5 rotor's C_p , or efficiency (power relative to available power in the flow), can be derived on the flood tide as shown in Figure 3.10.2.6, and also relative to the FAST code predictions developed under Tasks 1 & 2.

Figure 3.10.2.6 AWPP Gen5 Composite Rotor Efficiency vs. Water Velocity

The IWT Gen5 rotor performance results indicate that the improved structural capability has been achieved at some performance sacrifice, but the composite blade design does achieve the nominal rating of 35kW mechanical at approximately 2.1 m/s, the RITE site standard for a 5m diameter rotor.

3.10.3 Summary of the In-water Test

In summary, the logistics for the in-water testing encompassed a significant 18-month effort by Verdant to achieve the task of testing at full-scale prototype level as required by the DOE AWPP contract.

All aspects of the final task were accomplished successfully. The dynamometry testing satisfactorily collected 240,000 data points. In post-processing, the data from the ADCPs and DynoDACS was synchronized and smoothed, and utilized for performance analysis. The rotor structural performance was proven, with further processing of the in-water blade strain gage data (outside this contract) ongoing.

The composite rotor operating characteristics – rotor power curves and rotor efficiency – were determined and confirm the primary objectives of the DOE AWPP contract. The assessment of the improved structure and fabrication of larger, higher-power rotors was completed and the results indicate that all structural integrity, cost-effective fabrication, longevity, and scalability targets have been met, and that the rotor efficiency is on the pathway to commercial capability.

Additionally, advancements in demonstrating the efficacy of environmental monitoring protocols and the compatibility of the axial rotor design have been achieved, which is a critical success factor for any MHK system.

4. Products & Technology Transfer

The following products and technology transfer have occurred under the project.

4.1 Publications

- [1] - “A Hydrodynamic Optimization Method and Design Code for Stall-Regulated Hydrokinetic Turbine Rotors,” D. Sale, J. Jonkman, W. Musial; OMAE2009; May/June 2009
- [2] - “Detailed Inflow Measurements for Kinetic Hydropower Systems In a Tidal Strait,” J. Colby, D. Corren; HydroVision 2010 [*on Verdant Power RITE Project website: <http://www.theriteproject.com>*]
- [3] - “Inflow Measurements in a Tidal Strait for Deploying Tidal Current Turbines – Lessons, Opportunities and Challenges,” Y. Li, J. Colby, N. Kelley, R. Thresher, B. Jonkman, S. Hughes; OMAE2009-0911; June 2010
- [4] - “Hydrodynamic Analysis of Kinetic Hydropower Arrays,” J. Colby, M.A. Adonizio; Waterpower XVI [*July 2010 but undated*]; [*on Verdant Power RITE Project website: <http://www.theriteproject.com>*]

- [5] - "Hydrodynamic Analysis," J. Colby; Marine Technology, Society of Naval Architects and Marine Engineers; July 2010
- [6] - "Multi-scale Analysis of Kinetic Hydropower Arrays," J. Colby; Journal of Ocean Technology, vol. 6 no. 2; 2011
- [7] - "Numerical simulation of 3D flow past a real-life marine hydrokinetic turbine" [*note: Gen4 KHPS*], S. Kang, I. Borazjani, F. Sotiropoulos, J. Colby; Advances in Water Resources [*paper has been accepted for publication*]; December 2011
- [8] - "Building up the Tidal Strait!" J. Colby; IEC e-tech; January/February 2012
- [9] - "ADV measurements for turbulent inflow characterization in the East River New York City," B. Gunawan, V. Neary, J. Colby; Global Marine Renewable Energy Conference (ORNL/VP poster presentation); April 2012
- [10] - "Energy Generation and Transmission," Jonathan Colby; IEC e-tech; November 14th, 2012

4.2 Website/Internet Sites that Reflect Project Results

No specific project results were posted on the internet. General mention of the effort is made on Verdant Power's corporate website (www.verdantpower.com).

4.3 Networks or Collaborations Fostered

Throughout the course of the project, collaborations with the following partners have advanced scientific methods in support of the MHK industry:

- Scott Hughes, National Renewable Energy Laboratory – Adaptations of FAST model and blade static and fatigue testing
- Joshua Paquette, Sandia National Laboratories – CFD evaluation of composite blade shapes
- C.P. van Dam, University of California, Davis – Computer simulation of FEA loads
- Fotis Sotiropoulos, University of Minnesota St. Anthony Falls Laboratory – CFD and physical modeling
- Vince Neary, Oak Ridge National Laboratory – Advanced in-water measurements for turbulence evaluation

The above have provided advancement of MHK tools and technical know-how fostering sound collaborations for design advancement, not only for the benefit of the specific Verdant design under this contract, but for adaptation to other MHK technology development.

For the MHK manufacturing and supply chain, through the efforts of Jeff Calkins of MRI acting as Verdant's manufacturing Production QMS advisor, Verdant has established a composite blade manufacturing supply chain partner with Energetx Composites. This collaboration has fostered an advancement of a US-based MHK supplier as a critical success factor in the economics of commercial applications.

In the execution of the environmental monitoring work for the IWT, a potential future partnership with the Applied Research Laboratory (APL) at Penn State University was identified as a possible collaboration opportunity to assist in the video interpretation and data analysis techniques for DIDSON video of operating KHPS. This ongoing environmental monitoring technique could potentially be improved with application of video screening code to identify potential KHPS blade-fish interaction.

4.4 Technologies/Techniques

The following technologies and techniques were advanced during the execution of this contract:

- Computer codes for designing and analyzing axial-flow rotors
- Modification and validation of the FAST wind codes and TurbSim for MHK, conducted under Tasks 1, 2 and 3 - See Table 5.1 for summary
- ADV measurements on turbulence and power spectrum, under Task 6c - See ORNL/Verdant technical poster presentation - REF[9]

4.5 Inventions/Patent Applications, Licensing Agreements

As reported by Verdant Power in the Quarterly Technical Progress Reports submitted during the course of the project, the work conducted under this contract award produced activity related to the following inventions and potential future patent applications:

- Cavitation-resistant rotor design
- New blade filling process

Verdant also hereby reports two additional technology areas for potential future patent applications as a result of work conducted under this contract award:

- Novel Blade/hub root shape
- Water velocity measurement methodology

To the extent Verdant Power formally advances any of these patent applications, the company will disclose that activity and its results to the DOE contracting office as required.

4.6 Other Products

No other products as defined were produced.

5. Computer Modeling

This project utilized computer modeling, but development of new codes was not the primary function. A summary of existing NREL design codes utilized by Verdant Power is shown on Table 5.1 below

Table 5.1 NREL Computer Codes Supporting Verdant Power AWPP Project

	NREL WT_Perf	NREL FAST
a. Model description, key assumptions, version, source and intended use	WT_Perf uses blade-element momentum (BEM) theory to predict the performance of wind turbines. It is a descendent of the PROP code originally developed by Oregon State University. Portal website for code and information: [http://wind.nrel.gov/designcodes/simulators/wtperf/]	The NREL FAST (Fatigue, Aerodynamics, Structures, and Turbulence) Code is a comprehensive aeroelastic simulator capable of predicting both the extreme and fatigue loads of two- and three-bladed horizontal-axis wind turbines (HAWTs). Portal website for code and information: [http://wind.nrel.gov/designcodes/simulators/fast/]
b. Performance criteria for the model related to the intended use	WT_Perf simulates the performance of wind turbine rotors for given inflow conditions	FAST simulates extreme and fatigue loads of a modeled turbine, with a turbulent inflow generated by TurbSim, one of a number of sub-routines (preprocessors) within the FAST code.
c. Test Results to demonstrate the model performance criteria were met (e.g., code verification/validation, sensitivity analyses, history matching with lab or field data)	WT_Perf is used in many studies and papers to predict rotor performance. A general description is here: [http://wind.nrel.gov/designcodes/papers/CP-500-23975.pdf]	The following website has information on validation studies: [http://wind.nrel.gov/designcodes/simulators/fast/verification/] Moments obtained through strain measurements, and rotor torque data obtained with a load cell, during in-water tests performed in this project have been compared to predictions from a modified version of FAST for MHK applications.

	NREL WT_Perf	NREL FAST
d. Theory behind the model, expressed in non-mathematical terms	<p>Blade element moment theory is the basis for the code.</p> <p>Blade element theory models a blade as a set of separate 2D- blade elements (foils) aligned along the span of the blade from root to tip. A steady-state inflow is applied to the aerodynamic (hydrodynamic) properties of each foil, with no radial flow, to provide lift and drag forces, which are then integrated to find thrust and torque for the full blade and rotor. WT_Perf was run within HARP_Opt, a genetic algorithm (GA) to optimize blade geometry and performance.</p>	<p>The FAST (Fatigue, Aerodynamics, Structures, and Turbulence) Code is a comprehensive aeroelastic simulator capable of predicting both the extreme and fatigue loads of two- and three-bladed horizontal-axis wind turbines (HAWTs). The FAST code models the wind turbine as a combination of rigid and flexible bodies. FAST uses Kane's method to set up equations of motion, which are solved by numerical integration. The implemented method makes direct use of the generalized coordinates, eliminating the need for separate constraint equations. Refer to the FAST website for more information: [http://wind.nrel.gov/designcodes/simulators/fast/] The TurbSim preprocessor was used to provide stochastic inflow turbulence. Information available at: [http://wind.nrel.gov/designcodes/preprocessors/turbSim/]</p>
e. Mathematics to be used, including formulas and calculation methods	<p>Mathematical basis can be found here: [http://wind.nrel.gov/designcodes/papers/WilsonLissaman_AppAeroOfWindPwrMach_1974.pdf]</p>	<p>User Guide: [http://wind.nrel.gov/designcodes/simulators/fast/FAST.pdf]</p>
f. Peer Reviews - whether or not the theory and mathematical algorithms were peer reviewed, and, if so, include a summary of theoretical strengths and weaknesses	<p>Extensive use in wind industry with many peer reviewed technical publications</p>	<p>Extensive wind industry use and feedback. In addition to use and validation, FAST with AeroDyn was evaluated by Germanischer Lloyd WindEnergie and found suitable for "the calculation of onshore wind turbine loads for design and certification." Electronic versions of the issued certificate and report are available for viewing: [http://wind.nrel.gov/designcodes/papers/GL_Certific.pdf] [http://wind.nrel.gov/designcodes/papers/GL_Report.pdf]</p>
g. Hardware requirements	PC	PC
h. Documentation (e.g., users guide, model code).	<p>User Guide: [http://wind.nrel.gov/designcodes/simulators/wtperf/WT_Perf_Users-guide.pdf]</p>	<p>User guides: [http://wind.nrel.gov/designcodes/simulators/fast/FAST.pdf] [http://wind.nrel.gov/designcodes/preprocessors/turbSim/TurbSim.pdf]</p>