DEVELOPMENT TEST PLAN FOR BUDGET PERIOD 2

ADVANCED TIDGEN® POWER SYSTEM

DOCUMENT NUMBER: D-TD20-10152

REVISION 01 – APRIL 24, 2018

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Revision History

Revision	Rev. Date	Description	Originator	Approver
00	4-10-2018	Initial release	C. Marnagh	-
01	4-24-2018	Introduction added, schedule updated	C. Marnagh	J. McEntee

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1 Purpose

This document provides the high-level plan for the major development testing to be performed in Budget Period 2, as deliverable D5.4 of the U.S. Dept. of Energy (DOE) sponsored project:

Award No.:	DE-EE0007820, effective 11/1/2016
Project Title:	Advanced TidGen® Power System
Prime Recipient:	ORPC Maine
Principal Investigator:	Jarlath McEntee, P.E.

2 Development Test Overview

Budget Period 2 (BP2) will entail subsystem testing focused on refining design models and risk mitigation, ending with a full system verification installation in Cobscook Bay. The test program will be based on a sequential approach that addresses conservative design factors based on DNV GL standards to reduce likely overdesign in the system.

In 2018, efforts will primarily focus on composite development and production of the first turbine assembly, targeting barge testing for performance and drag loads. Composite analysis will refine characterization models for the selected material sets and begin an accelerated life testing program focused on high stress areas of the turbines. Loading results from turbine testing will inform cumulative damage models to quantify anticipated component life of the composite turbines. Results will also hone-in our assumptions to reduce both structure and weight, particularly for anchor requirements. Post-test inspection data will be compared to characterization testing results prior to production of the full system set of turbines.

Primary activities in 2019 will focus on model-scale anchor evaluation in Western Passage and deployment system testing. Anchor holding efficiency estimates will be derived from the model-scale testing, which will be used as well to reduce conservative design assumptions and overall anchor weight. The results will inform full-system anchor design as well as the test mooring requirements for the deployment system testing. The deployment system testing will target critical operational risks, such as near-shore anchor construction, connections between the mooring system and TidGen® TGU (turbine generator unit – the device without the mooring system and electrical transmission infrastructure). Development and verification of assembly, launch and deployment procedures, in terms of operational safety and risks, are priorities of the testing.

DNV GL will be utilizing testing activities and full system integration to complete several steps in the certification process, including final design assessments, manufacturing and transportation assessments, and full system test plan certification.

3 Development Tests

The following overviews development test activities for the DOE Advanced TidGen® Project.

3.1 Turbine load / performance testing

- **Components under test:** Turbine and fairing structure. The turbine will be the first build of the TidGen® 2.0 turbine.
- **Description:** This test includes a single full-sized turbine mounted in a controlled environment (on a test barge) to measure single turbine loads. The test barge will be subject to a range of inflow velocities which will also be measured. The general test set-up is similar to previous ORPC tests, with load cells added to a holding frame as the primary measurement instruments. (Reference Figure 1.)
- **Objectives:** A performance curve will be generated and drag loads will be measured to reduce conservative design assumptions primarily for the mooring system requirements, especially for anchor holding capacity. CFD models will be refined. As part of the composite development effort, the turbine will be inspected before and after

operation to assess any degradation of the composite structure, particularly for the impact of manufacturing defects under operational loading.

- **Key risks:** Integrity and performance of first composite turbine build; sensor/instrumentation package for load measurements.
- **Schedule:** Testing is targeted for Q4 2018 through Q1 2019.
- **Facilities, equipment & resources:** Barge testing will occur off the coast of Maine, in either Cobscook Bay or Castine, Maine. Equipment includes a test barge used by ORPC in prior projects for similar test purposes and power electronics / load for controlling the generator torque and dissipating power.

Figure 1. The turbine performance testing of the Advanced TidGen® turbines will be performed in a barge tow test similar to several tests performed by ORPC on earlier turbine designs.

3.2 Anchor-holding capacity validation

- **Components under test:** Model-scale gravity anchors.
- **Description:** Pull tests on scaled anchors (1 metric ton) at the deployment site will measure frictional forces between gravity anchors and bottom. Skirts and other potential modifications will be assessed. Several “pulls” will be performed around the deployment area. Primary measurements will be anchor position and applied mooring line loads. (Reference Figure 2.)

- **Objectives:** Anchor efficiency measurements will be used to reduce conservative design assumptions. The effect of skirts or other modifications will be assessed for effectiveness. The results will inform final anchor design, as well as the deployment subsystem testing to occur later in the year.
- **Key risks:** Bottom profile/interface uncertainty; sensor/instrumentation package for load measurements.
- **Schedule:** Testing is targeted Q1 to Q2 2019.
- **Facilities, equipment & resources:** Testing will occur at the deployment site area identified in Western Passage, off the coast of Eastport, Maine. Equipment includes a test barge and/or large boat with a crane capable of managing metric ton anchors.

Figure 2. Anchor pull testing will be performed off a boat capable of deploying a 1 metric ton anchor, with instrumentation capable of determining pull loads for holding capacity estimates.

3.3 System deployment & retrieval testing

- **Components under test:** Subsystem testing of buoyancy pod, bridle interface with mooring system, mooring system and anchor.
- **Description:** The testing will assess and verify the deployment and mooring system design including critical operations from onsite assembly, near shore assembly, transit, and deployment offshore. A section of the buoyancy pod will utilize the bridle and mooring system rigging to smaller scale anchors. The test well replicate ORPC's prior deployment of the 2014 OCGen® buoyant tensioned mooring system project sponsored by the U.S. Dept. of Energy. A deployment rig with external equipment, such as winches and float bags, will be assessed for safety and functionality, as well as the connecting and detachment of anchors in critical operations during deployment and retrieval. The system will be moored over a short duration to verify dynamic stability and predicted movements of the system throughout a tidal cycle. (Reference Figure 3.)
- **Objectives:** The test will verify the bridle and mooring system interface design, and of attachment and detachment methods. Critical operations will be verified for anchor

deployment, system launch, and on-water operations of external equipment. Tooling requirements for full system deployment will be finalized.

- **Key risks:** New component interfaces, offshore attachment/detachment operations, bridle functionality throughout tidal cycle, test anchor holding capacity.
- **Schedule:** Testing will be performed in Q3 2019.
- **Facilities, equipment & resources:** The test will require a deployment site with launch ramp and required crane for test system assembly and launch, either in Cobscook Bay or Western Passage. A tug and barge outfitted with winches will be used for transit and offshore deployment and retrieval.

Figure 3. Potential test system for the deployment and retrieval subsystem test. Diver is included only for size reference, as it is not anticipated that a diver will be required except for near shore connections to the anchors. Anchors will be gravity anchors of undetermined design.

3.4 Composite structural testing & accelerated life testing

- **Components under test:** Composite coupons of candidate material sets, critical high stress structural sections of the turbine (foil/strut joint)
- **Description:** Static and dynamic (fatigue) testing will be performed on carbon fiber/glass fiber epoxy laminates, one with hydrophilic resin and the other with hydrophobic resin, for further characterization of failure mechanisms of saturated composites under representative loading. Water uptake and diffusion rates will be analyzed, along with

the impact on resin to fiber bonding, both for carbon and glass fibers. The impact of typical manufacturing defects on material degradation will be characterized, particularly with respect to water uptake, stress concentrations and static and dynamic failure. A second phase of testing will be an extensive accelerated life program for the finalized turbine composites towards development of component life models, to be performed in parallel with on-water system installations. (Reference Figure 4).

- **Objectives:** Testing will inform final composite designs of the second through eighth TidGen® turbines, along with inspection of the first turbine after its performance testing. Cumulative damage models will be developed, for utilization and validation for eventual full system deployments.
- **Key risks:** Durability of composite material sets determined from accelerated life testing; inadequate manufacturing quality or process control methods; inability to get statistically significant results
- **Schedule:** Testing will occur over an extended duration, from Q3 2018 through Q2 2020.
- **Facilities, equipment & resources:** Coupons will be produced by the turbine manufacturer and tested at laboratory facilities at CERL (Composites Engineering Research Laboratory) and Montana State University.

Figure 4. Coupon testing performed at Montana State Univerisity in budget period 1. Static and dynamic (fatigue) tension testing were performed as a preliminary evaluation of composite material sets in both dry and saturated (aged) states. Efforts in budget period 2 will focus on two material sets for comprehensive characterization of failure in accelerated life testing.

3.5 Composite turbine joint testing

- **Components under test:** Candidate joint geometries of foil to strut connection
- **Description:** Structural testing will be performed prior to and during the first turbine build to evaluate structural integrity and fatigue performance.
- **Objectives:** Determine the best joint geometry in terms of durability for the composite turbine from a selection determined by ORPC and the manufacturer.

- **Key risks:** Primary risks are schedule and manufacturer's resources to perform sufficient testing for evaluation prior to the first turbine build; results of test may require an additional turbine to be built to replace the first one for the final system integration.
- **Schedule:** Q3 through Q4 2018
- **Facilities, equipment & resources:** Testing will be performed either at the manufacturer's facility or at Montana State University.

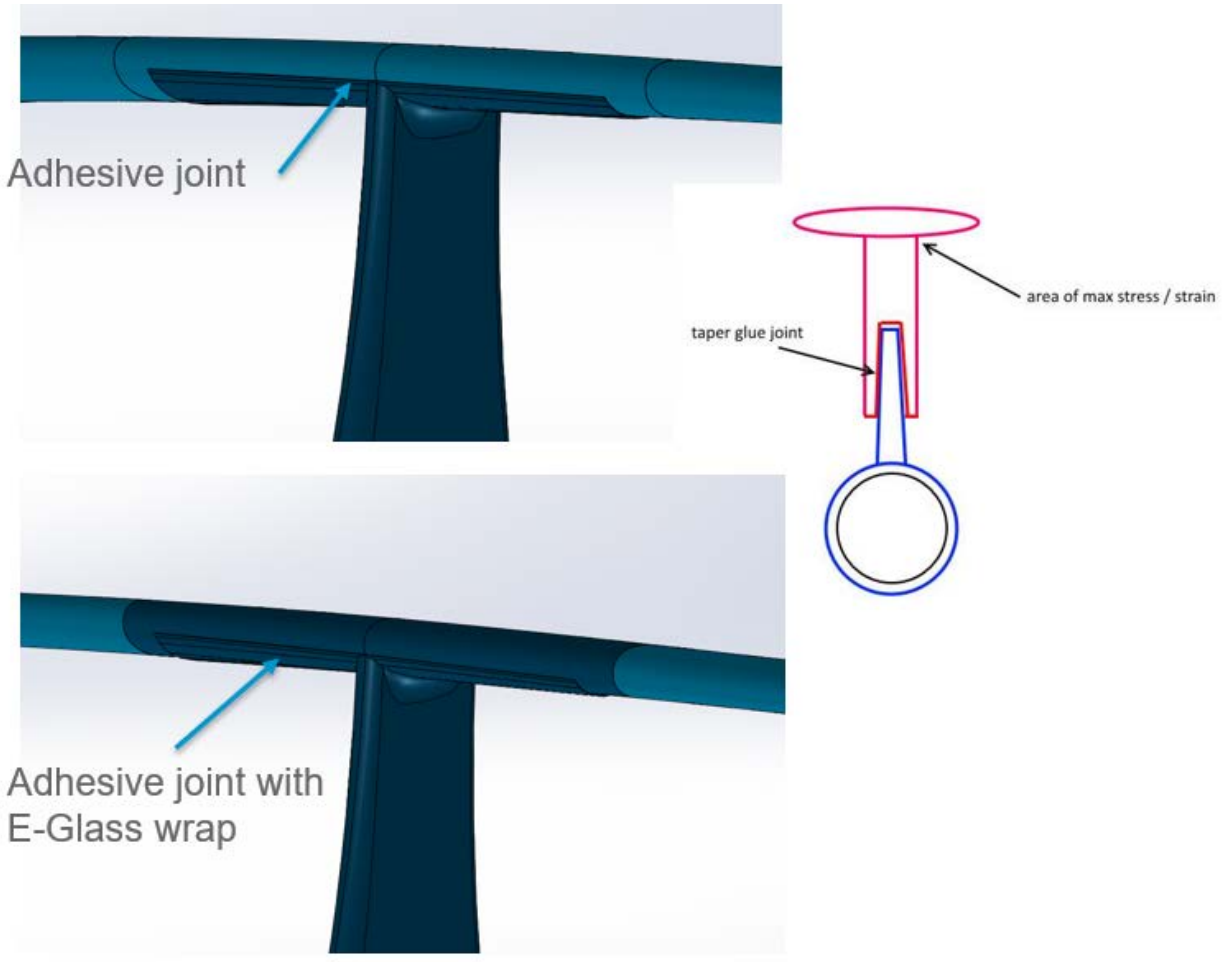

Figure 5. Potential bonded joints between foil and strut. Joint testing would be performed by the manufacturer to verify predicted structural properties prior to the first turbine build.

3.6 Full system verification deployment in Cobscook Bay

- **Components under test:** Full TidGen® system with mooring system adapted for Cobscook Bay's shallower depths and seabed type.
- **Description:** The system will be fully integrated and deployed at the lower flow resource in Cobscook Bay, where ORPC had previously deployed its first-generation system in 2013. The system will be validated and verified throughout the concept of operations, from supply chain through onsite assembly, deployment, operations and retrieval.

- **Objectives:** Validation of manufacturing, transportation, onsite assembly, launch, deployment and retrieval methods. Verification of system integration build, system shakedown, control system, instrumentation and SCADA systems. Verification of mooring system throughout tidal cycle. Verification of system performance throughout tidal cycle. Post-system inspection of components including composite turbines.
- **Key risks:** Risks are identified per the system FMEA; in addition, first time integration and operations have a higher likelihood of identifying design and operational issues requiring modification or major redesign.
- **Schedule:** Q2 2020
- **Facilities, equipment & resources:** Prepared deployment site; all required tooling for assembly, launch and deployment/retrieval; electrical infrastructure for grid transmission.

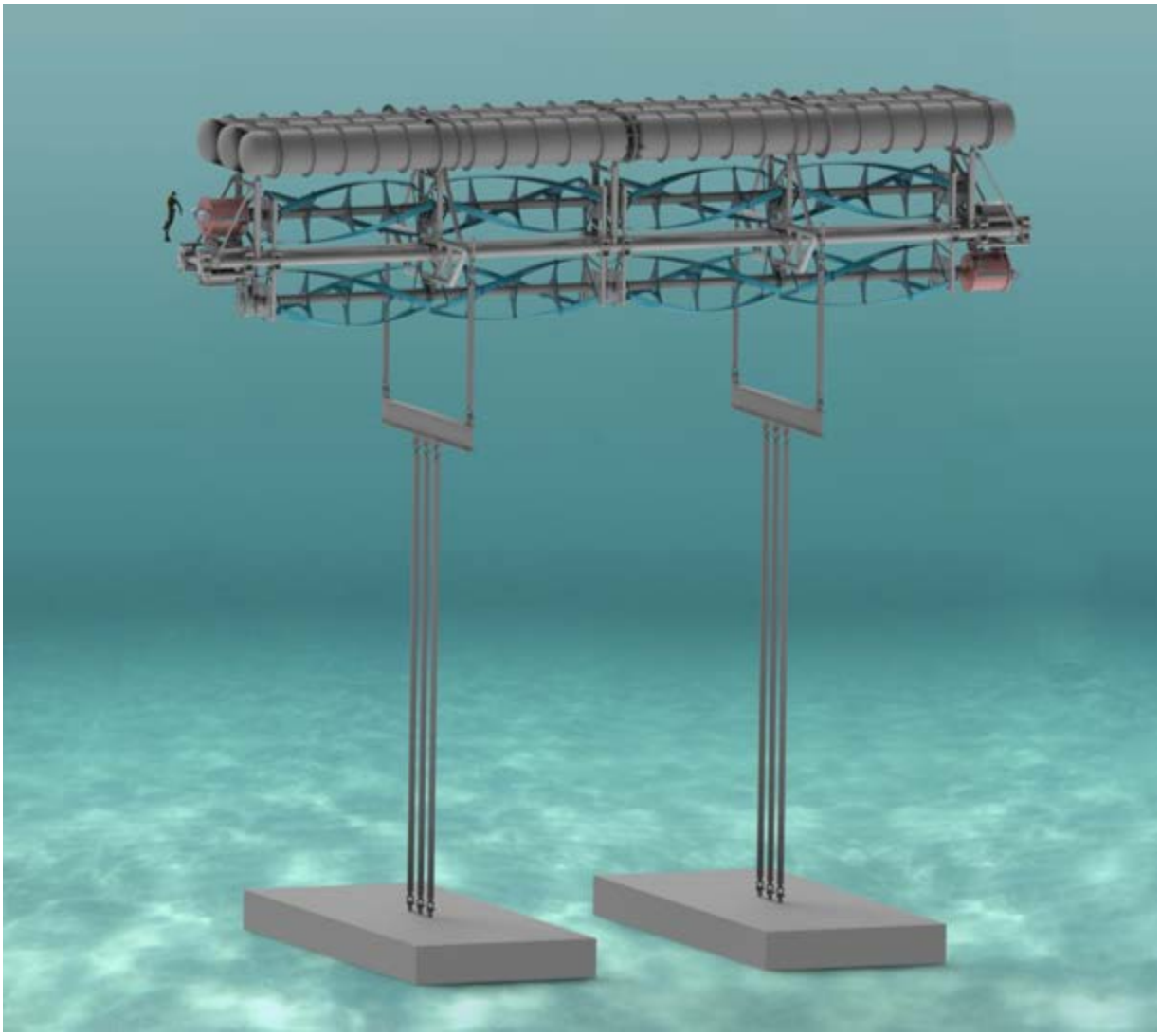

Figure 6. Full system design, to be deployed first in the low-flow resource at Cobscook Bay for system verification.

3.7 Notes on Additional Testing

Note that the driveline design concept was validated in a prior project sponsored by the U.S. Dept. of Energy. The testing was performed at the University of Maine ASCC in 2017, consisting of a driveline configuration with bearing housings encapsulated with water, and operated under representative full loads measuring deflections, torque and heat losses, including under induced misalignment. Critical outcomes were driveline frictional measurements and temperature changes under various loading conditions.

The full system validation installation will occur from Q3 2020 through Q4 2021 in Western Passage.

4 Schedule

The following is the anticipated schedule for performing the development tests.

ID	Task Name	Duration	Start	Finish	Predecessors
1	**Turbine load / performance testing**	**130 days**	**Mon 7/2/18**	**Fri 12/28/18**	
2	Build and test prep	5 mons	Mon 7/2/18	Fri 11/16/18	
3	Conduct tests	1.5 mons	Mon 11/19/18	Fri 12/28/18	2
4	**Anchor-holding capacity validation**	**80 days**	**Mon 12/31/18**	**Fri 4/19/19**	
5	Build and test prep	3 mons	Mon 12/31/18	Fri 3/22/19	3
6	Conduct tests	1 mon	Mon 3/25/19	Fri 4/19/19	5
7	**System deployment & retrieval testing**	**170 days**	**Tue 1/1/19**	**Mon 8/26/19**	
8	Build and test prep	7 mons	Tue 1/1/19	Mon 7/15/19	
9	Conduct tests	1.5 mons	Tue 7/16/19	Mon 8/26/19	8
10	Composite structural & coupon testing	4.5 mons	Mon 7/2/18	Fri 11/2/18	
11	Composite accelerated life testing	12 mons	Mon 11/5/18	Fri 10/4/19	10
12	Composite turbine joint testing	2 mons	Mon 7/2/18	Fri 8/24/18	
13	**Full system verification in Cobscook Bay**	**200 days**	**Wed 8/21/19**	**Tue 5/26/20**	
14	System integration	8 mons	Wed 8/21/19	Wed 4/1/20	15SF
15	Deploy in CB	2 mons	Wed 4/1/20	Tue 5/26/20	
16					
17	**Full system validation deployment in Western Passage**	**91 days**	**Wed 5/27/20**	**Wed 9/30/20**	
18	Site and system preparation	4.5 mons	Wed 5/27/20	Tue 9/29/20	15
19	Deploy TidGen® in Western Passage	0 days	Wed 9/30/20	Wed 9/30/20	18FS+1 day