EE0007248 - The Design and Development Of a Composite Hydropower Turbine Runner

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
ENGINEERED MATERIAL SOLUTIONS

PennState
Applied Research Laboratory

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and

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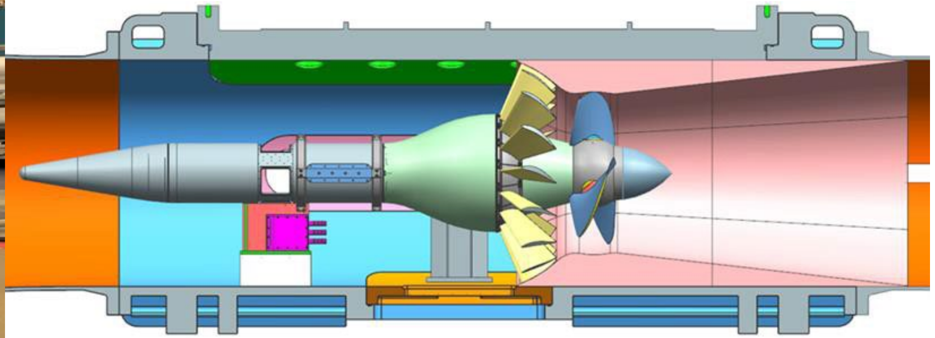

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Project Overview

Project Summary

- DOE objective: Design and test new and innovative conventional hydropower powertrain components
- Project goal: Verify that composite materials are a reliable and economic alternative to traditional metallic runners to reduce costs and increase energy capture.
- Develop cavitation-resistant coatings
- Prototype and test a composite runner system under real-world hydropower turbine operating conditions.

Intended Outcomes

- Prototype a weight-efficient, fatigue resistant, low-maintenance turbine runner using composite materials to reduce mass and extend service life
- Improve runner reliability by developing a high-performance coating system that resists cavitation and sediment erosion
- Provide performance test data of the composite runner/coating in true hydropower turbine operating conditions

Project Information

Principal Investigator(s)

Mr. Paul E. Fabian
Composite Technology Development, Inc.,
Lafayette, CO

Project Partners/Subs

- Penn State University – ARL
- Sandia National Laboratory
- Tribologix Inc.
- Voith Hydro, Inc.

Project Status

Completed

Project Duration

- July 1, 2016
- April 30, 2022

Total Costed (FY19–FY21)

$698,247

Project Objectives: Relevance

Relevance to Program Goals:

- This program addresses WPTO's mission of enabling research, development, testing and commercialization of new technologies to advance marine energy as well as next-generation hydropower and pumped storage systems for a flexible, reliable grid through the following:
  - Leverages new composite manufacturing and materials to dramatically lower costs of components and systems
    - Design and manufacture of composite hydroturbine runner
    - Developed new, higher performing liquid polymer resin system for runners as well as a cavitation resistant coating to increase longevity in operation
    - Both reduce costs through increased durability and expected lifetimes
  - Supports testing of new technologies (composite runners), including development of necessary testing infrastructure
    - Testing of composite runners in real-world environment
    - Fabrication of simulated hydroturbine inside ARL's water tunnel for advanced hydropower testing of components
  - Supports goal of utilizing advanced manufacturing and materials to reduce overall cost of energy/electricity

Project Objectives: Approach

Phased Program Approach

- Phase I
  - Develop system requirements
  - Perform materials assessment and cavitation coating development
  - Design a composite turbine runner
- Phase II
  - Fabricate composite hydroturbine blades
  - Perform composite blade mechanical testing to align
  - Fabricate composite hydroturbine runner set with cavitation coating
  - Perform scaled hydroturbine runner testing in ARL water tunnel
- Incorporated input from leaders in hydroturbine materials & testing
  - ARL/PSU
  - Sandia National Laboratories
  - Voith Hydro

Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

- Prototyped a weight-efficient, fatigue resistant, low-maintenance turbine runner using composite materials to reduce mass and extend service life
- Improved runner reliability by developing a high-performance coating system that resists cavitation and sediment erosion
- Provided performance test data of the composite runner/coating in true hydropower turbine operating conditions

Outcomes:

- Further interest by Hydropower community in using advanced composite materials
- Commercial sales of new materials for use in hydropower applications
- Prototype production and field trials by major hydropower commercial partner
- Commercial large-scale production and use of design and materials in hydro applications resulting in lower cost electricity

Project Budget

Total Project Budget – Award Information		
DOE	Cost-share	Total
$1,124.4K	$499.5K	$1,623.9K

FY19	FY20	FY21	Total Actual Costs FY19–FY21
Costed	Costed	Costed	Total Costed
$223.5K	$179.5K	$295.2K	$698.2K

- Phase I (Year 1) started in late 2016
- Phase II (Year 2) work was extended into FY19 due to delays in blade production and water tunnel modification work delays
- Phase II work was further delayed by COVID and resulting shutdown of facilities and availability of personnel. Work was restarted in FY21.
- Additional funding by DOE was provided in FY20 due to increased costs for fabricating water tunnel hardware and performing testing at ARL

End-User Engagement and Dissemination

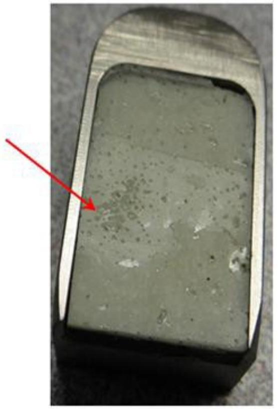
- Program was initiated with a commercial stakeholder, Voith Hydro, as a partner in design and development
  - Proprietary blade design was supplied by Voith as a baseline
    - Allowed direct comparison to stainless steel material properties
    - Provided operational parameters used to set metrics for testing of composite blades
    - All information was proprietary so could not be shared with outside parties
  - Sandia National Laboratory (SNL), PSU/ARL, and Voith personnel were involved throughout the project and attended monthly program review meetings
    - Allowed regular advisement and input on program
    - Program team also participated in milestone meetings such as Requirements Review, Test Readiness Reviews, and Manufacturing Readiness Reviews
  - Voith included since they were our commercial manufacturing partner that allowed a direct path to the commercial market
  - PSU/ARL were the cavitation testing and water tunnel test experts who could enable simulated real-world test results
  - SNL acted as material coating experts
- Results have been shared with Voith Hydro for evaluation of next steps

Performance: Accomplishments and Progress

- Materials
  - Prior evaluation and screening tests in Year 1 identified materials to be used for water tunnel testing in Year 2
  - CTD-K08/K13916 high modulus carbon fiber provided necessary stiffness and performance to achieve mechanical properties desired for blade
  - CTD-133 coating was found to offer the best cavitation resistance in accelerated cavitation erosion testing conducted at PSU/ARL

Part Description	Material	Manufacturer
Hub interface	410 Stainless Steel	Various
Composite blade matrix	CTD-K08 resin	CTD
Composite blade fiber	K13916 carbon fiber	Mitsubishi
Hub to blade adhesive	EA9394	Loctite Hysol
Anti-cavitation coating	CTD-133	CTD

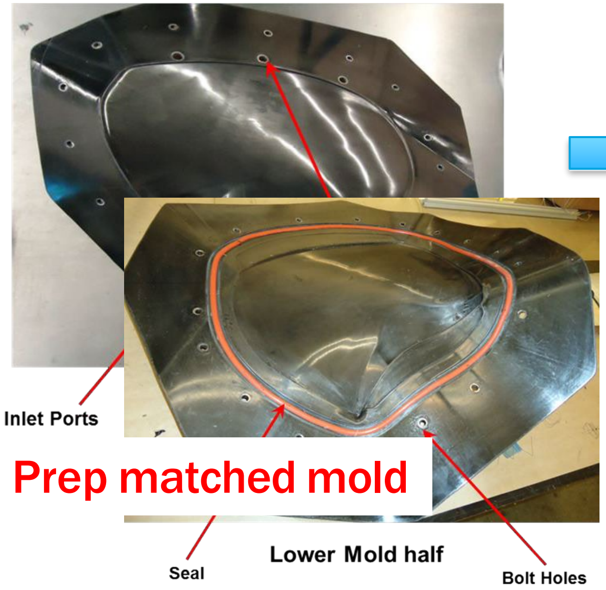
CTD Sample #5: Pre-test



CTD Sample #5: Post-test (300 min exposure)

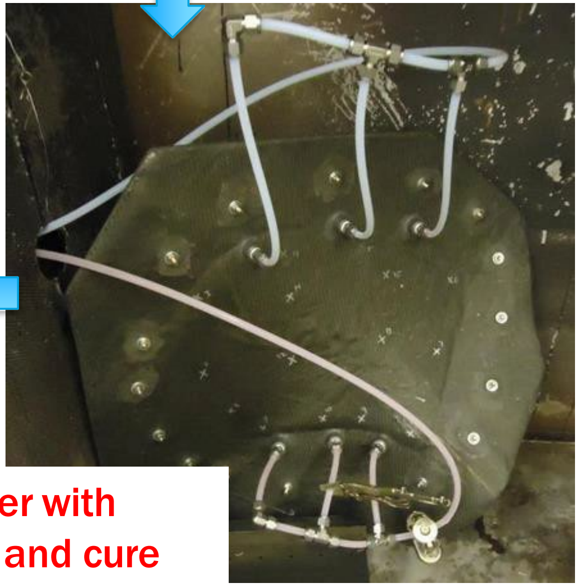
Performance: Accomplishments and Progress (cont.)

- Composite Blade Fabrication
  - Blades fabricated using Vacuum Assisted Resin Transfer Molding (VARTM) process
  - Post fabrication machining to achieve exact blade dimensions



Prep matched mold

Load carbon fiber plies into mold

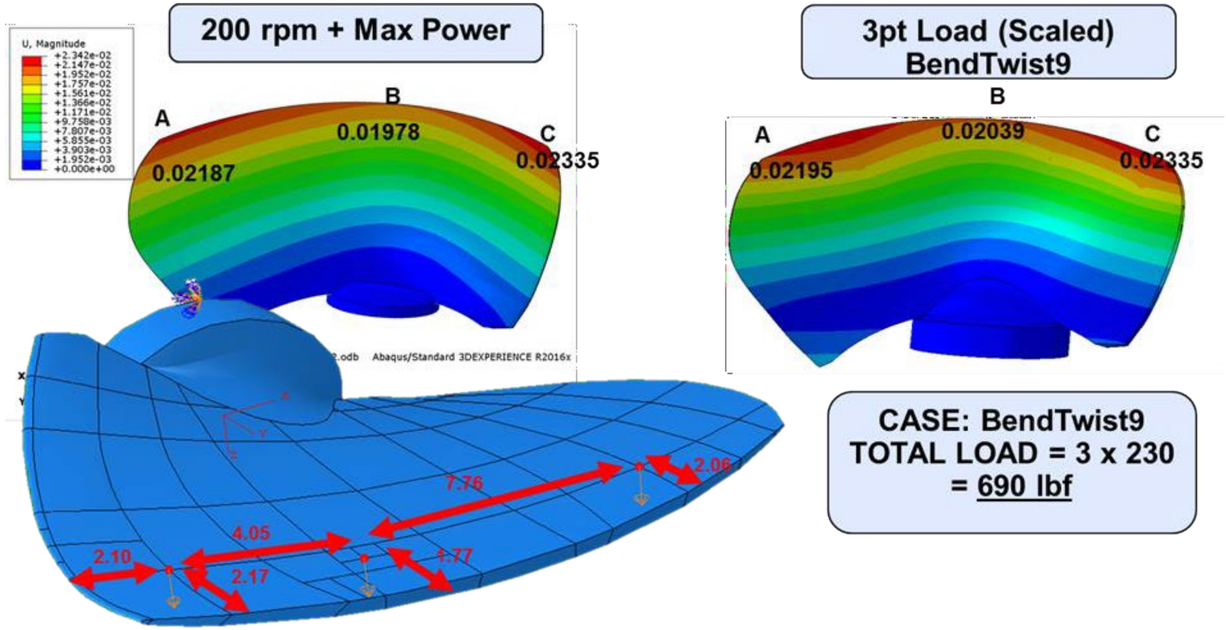


Impregnate fiber with CTD-K08 resin and cure

Machine to final dimensions

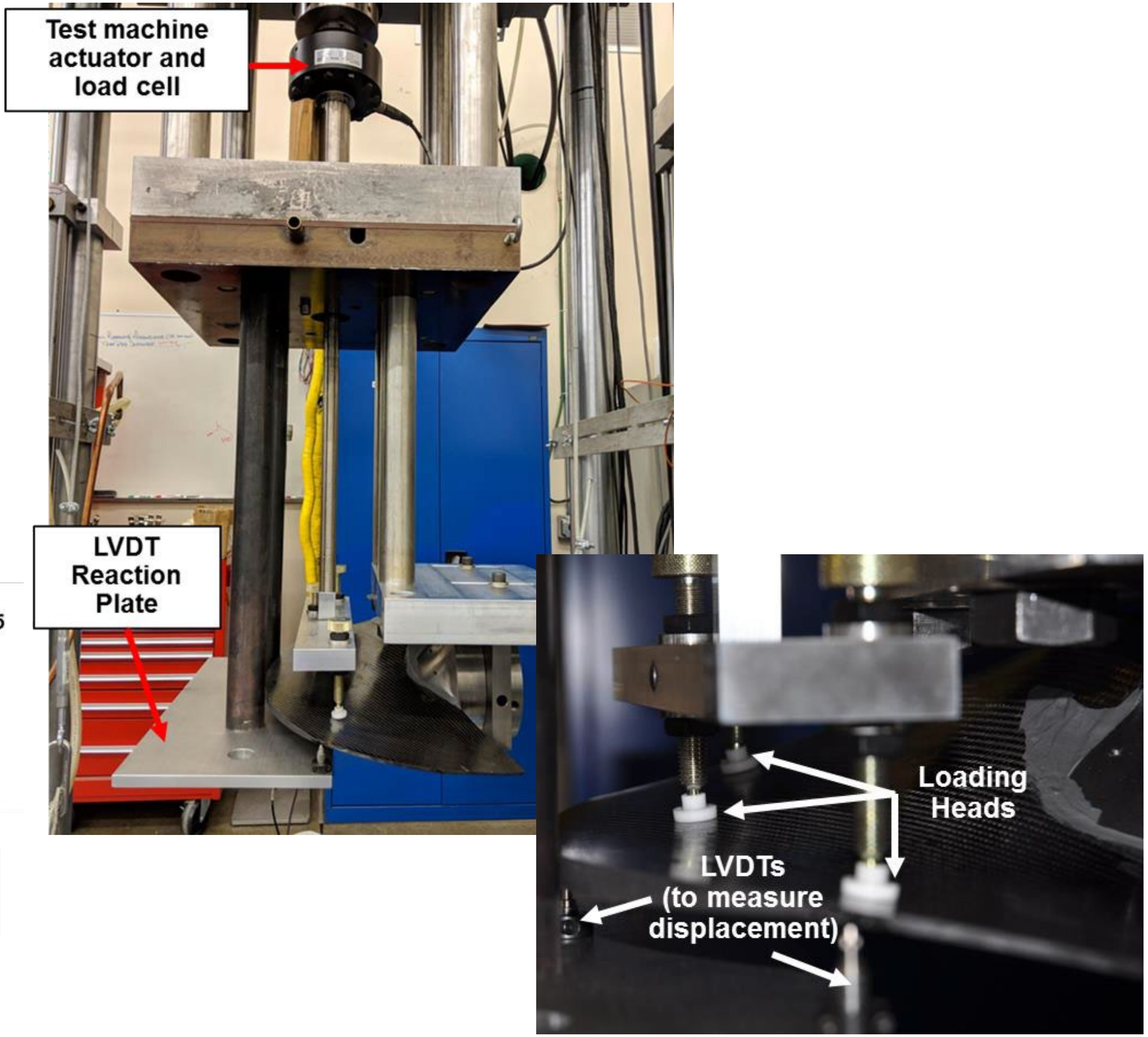
Performance: Accomplishments and Progress (cont.)

- Blade Prototype Testing Set-up
  - Blades tested in bending in fatigue and to failure
  - Point loading in servo-hydraulic test machine at room temperature in air
  - Test results matched to FEA results to validate composite blade performs as designed


200 rpm + Max Power

3pt Load (Scaled) BendTwist9

CASE: BendTwist9
TOTAL LOAD = 3 x 230
= 690 lbf



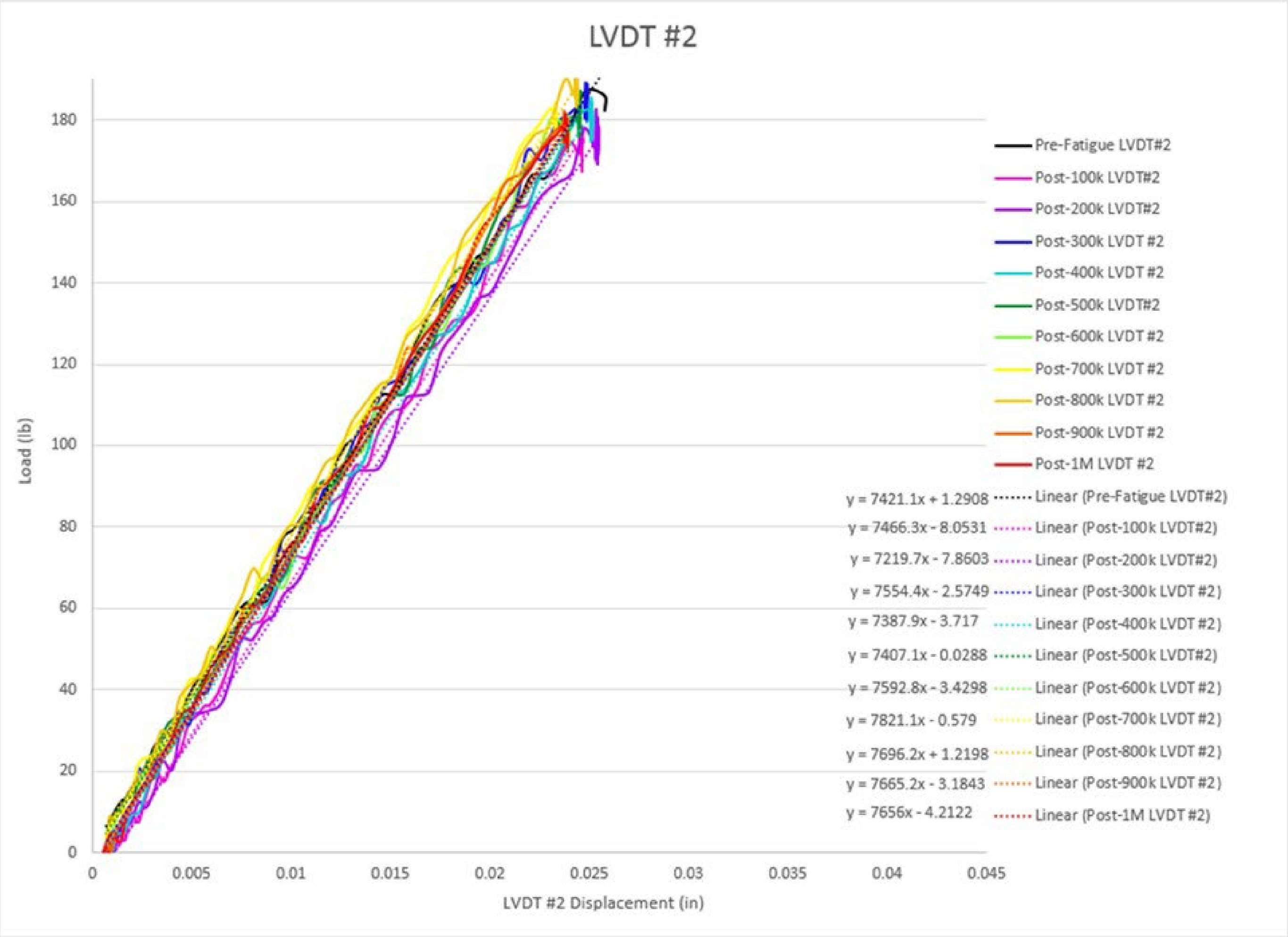
Performance: Accomplishments and Progress (cont.)

- Blade Prototype Testing Results
  - Deflection near tip of blade during operation biggest concern
  - Quasi-static test results matched FEM results
  - Fatigue testing at operating loads showed no degradation after 10^6 cycles
  - Failure loads averaged over 4,000 lb.
    - Factor of Safety of over 4 from loads for Maximum Power

Maximum Power Operating Condition

CASE	A	B	C
TEST: Raw LVDT Measurement	0.089	0.093	0.097
TEST: Compensated for Fixture Rotation	0.036	0.039	0.043
FEM: E1=67MSI	0.022	0.020	0.023
FEM: E1=52MSI & Modified Load Points	0.033	0.030	0.035

Load vs. Displacement up to 10^6 cycles

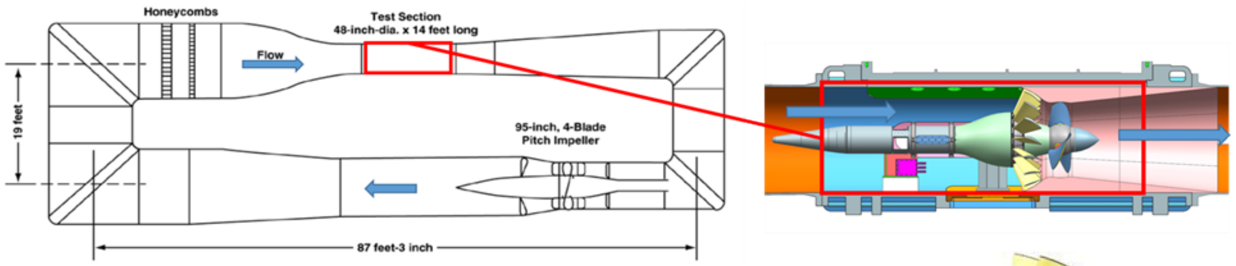


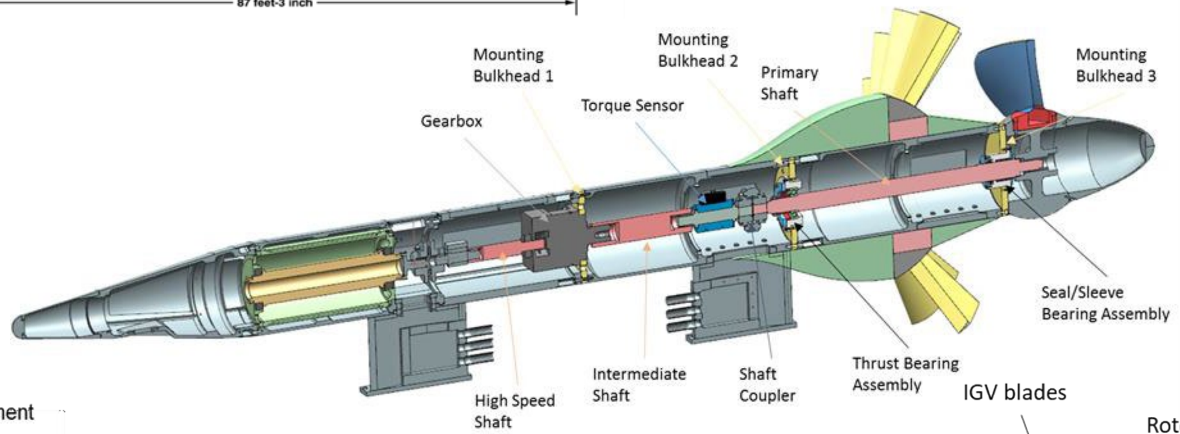
Performance: Accomplishments and Progress (cont.)

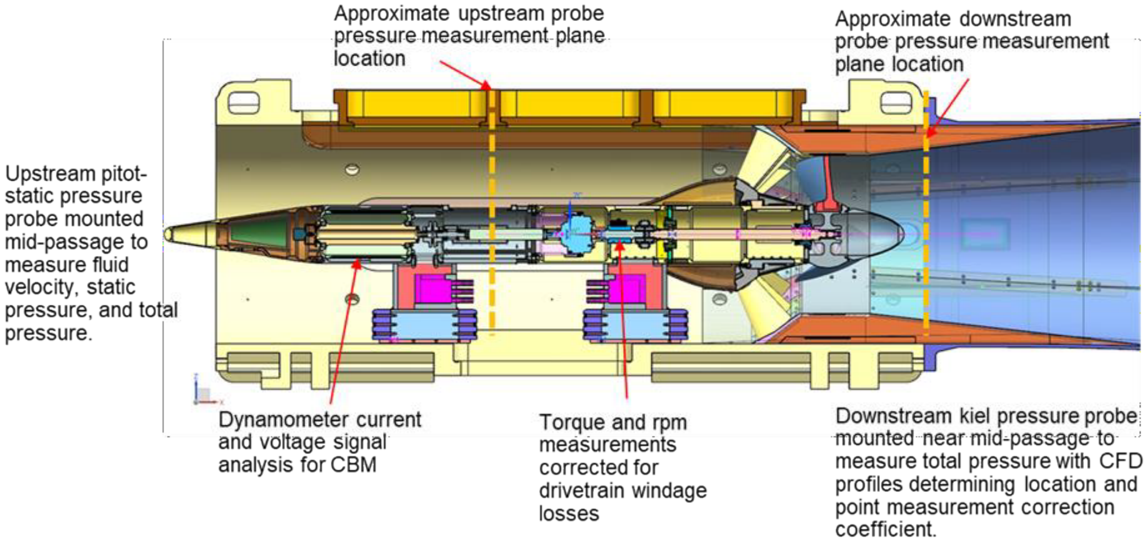
- Runner Set Fabrication
  - Runner set of 3 blades + 1 extra fabricated
  - Blades bonded and pinned to SS hub interface
  - CTD-133 anti-cavitation coating applied to outside surface of blade
  - Runner set shipped to PSU/ARL

Performance: Accomplishments and Progress (cont.)

- Turbine Runner Testing
  - Testing performed inside the Garfield Thomas Water Tunnel (GTWT) at PSU/ARL
  - A scaled (76%) version of the Voith Bulb Turbine system was fabricated and installed inside the water tunnel
  - Parts fabricated and installed in water tunnel







Approximate upstream probe pressure measurement plane location

Approximate downstream probe pressure measurement plane location

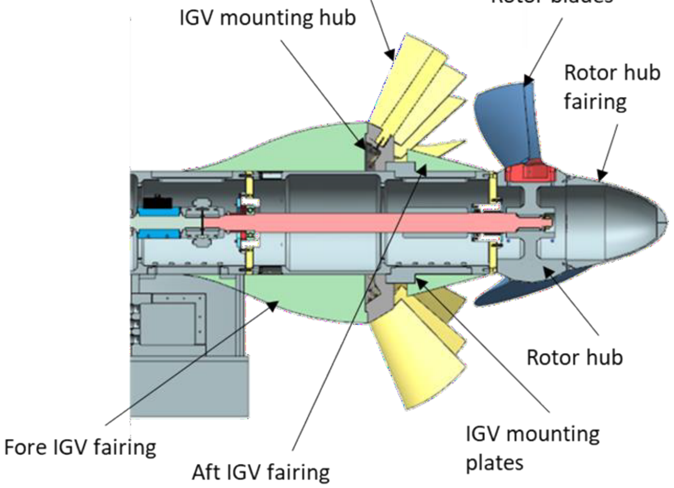
Upstream pitot-static pressure probe mounted mid-passage to measure fluid velocity, static pressure, and total pressure.

Dynamometer current and voltage signal analysis for CBM

Torque and rpm measurements corrected for drivetrain windage losses

Downstream kiel pressure probe mounted near mid-passage to measure total pressure with CFD profiles determining location and point measurement correction coefficient.

Operating Condition	Description
Maximum Efficiency	Operating at peak efficiency
Maximum Power	Operating at peak power extraction
Controlled Runaway	Maximum speed, blade angles fixed
Uncontrolled Runaway	Maximum speed, blade angles uncontrolled

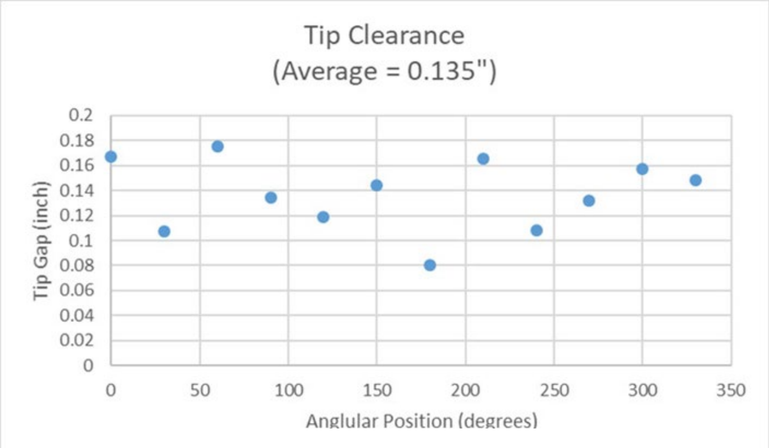


Performance: Accomplishments and Progress (cont.)

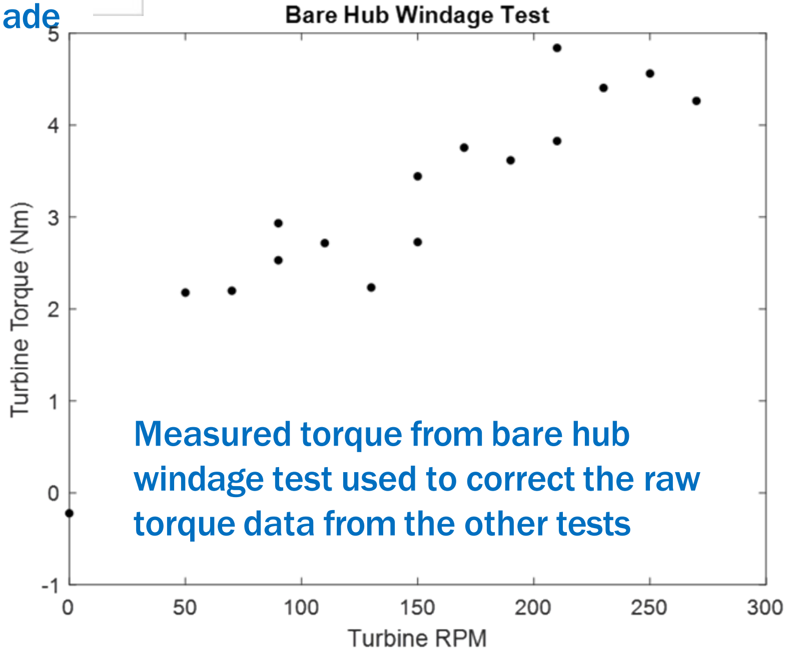
- Turbine Runner Testing
  - Installation of scaled Voith Bulb Turbine in GTWT

Performance: Accomplishments and Progress (cont.)

- Turbine Runner Testing
  - Test Plan
    1. Windage test - Remove rotor blades and vary rpm to measure drivetrain windage losses
    2. Hydrodynamic performance sweep - Hold flowrate constant and vary rpm
    3. Reynolds sweep - Vary flowrate and rpm by constant ratio
    4. Condition Based Maintenance (CBM) test - Simulate fault condition by removing IGV blade



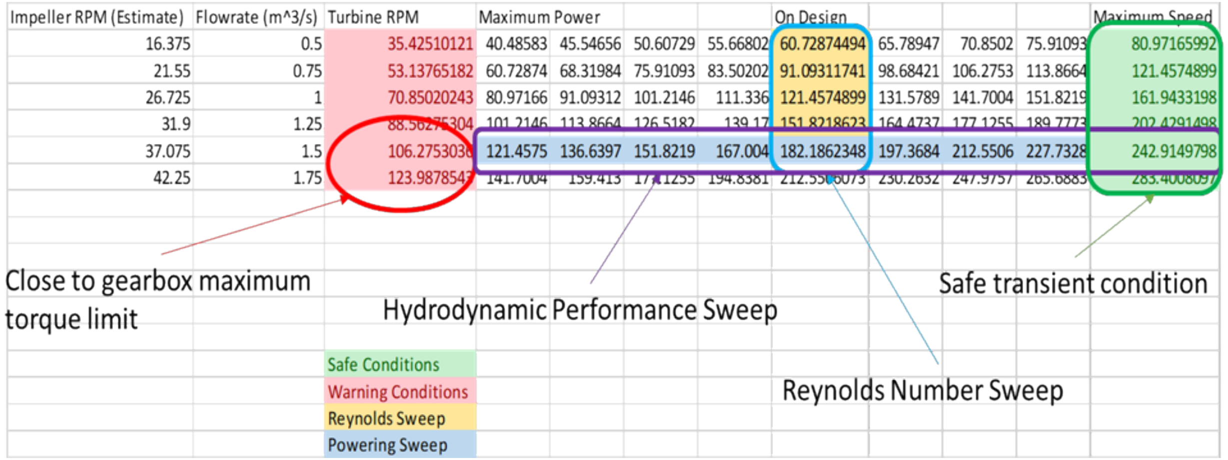
Tip clearance of tallest composite blade



Measured torque from bare hub windage test used to correct the raw torque data from the other tests

Performance: Accomplishments and Progress (cont.)

- **Turbine Runner Testing**
  - The key measurements required for the validation test were:
    - Flowrate, Q
    - Stagnation pressure change across turbine, $\Delta Pt = Pt1 - Pt2$
    - Turbine rotor rotational speed, N
    - Turbine rotor torque, τ



Impeller RPM (Estimate)	Flowrate (m^3/s)	Turbine RPM	Maximum Power				On Design				Maximum Speed
16.375	0.5	35.42510121	40.48583	45.54656	50.60729	55.66802	60.72874494	65.78947	70.8502	75.91093	80.97165992
21.55	0.75	53.13765182	60.72874	68.31984	75.91093	83.50202	91.09311741	98.68421	106.2753	113.8664	121.4574899
26.725	1	70.85020243	80.97166	91.09312	101.2146	111.336	121.4574899	131.5789	141.7004	151.8219	161.9433198
31.9	1.25	88.56275304	101.2146	113.8664	126.5182	139.17	151.8218623	164.4737	177.1255	189.7773	202.4291498
37.075	1.5	106.2753036	121.4575	136.6397	151.8219	167.004	182.1862348	197.3684	212.5506	227.7328	242.9149798
42.25	1.75	123.9878543	141.7004	159.413	17[illegible].1255	194.8381	212.55[illegible]6073	230.2632	247.9757	265.6883	283.4008097

Close to gearbox maximum torque limit

Hydrodynamic Performance Sweep

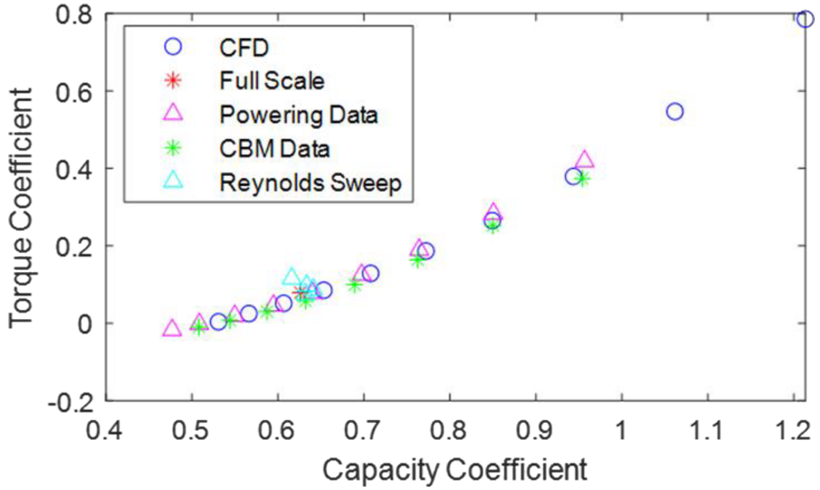
Safe transient condition

Reynolds Number Sweep

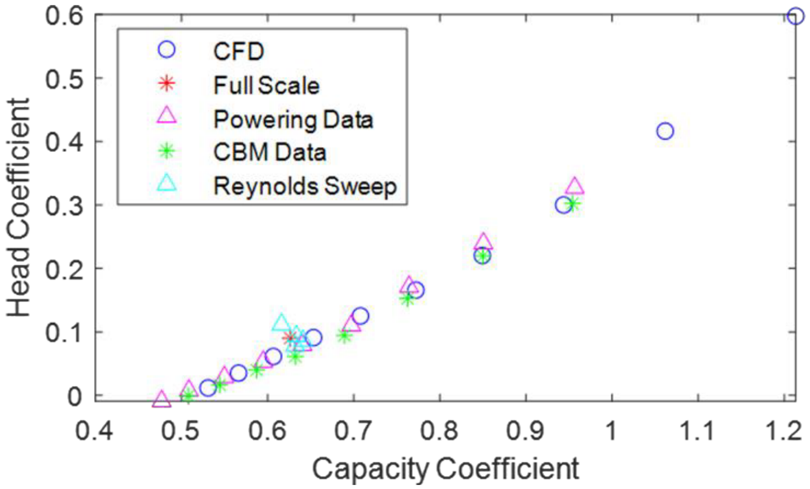
Safe Conditions
Warning Conditions
Reynolds Sweep
Powering Sweep

Test matrix for correct RPM and speed for safe operating conditions

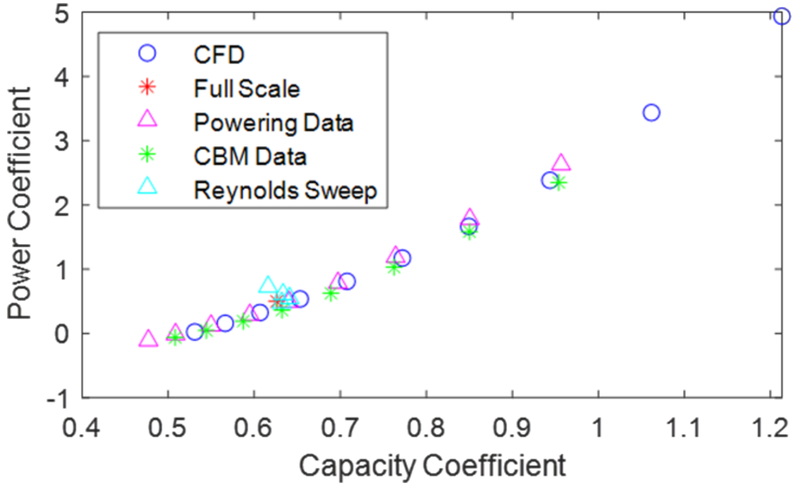
Hydrodynamic Performance Sweep Results



Torque Coefficient vs. Capacity Coefficient



Head Coefficient vs. Capacity Coefficient



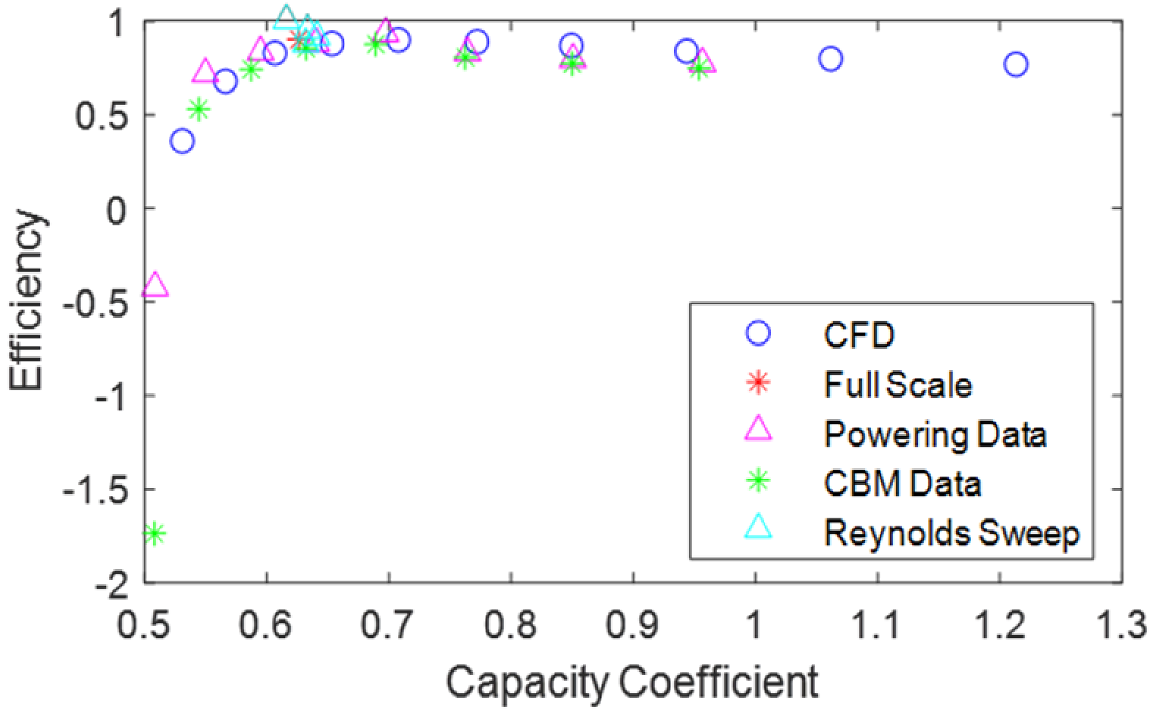
Power Coefficient vs. Capacity Coefficient

Performance: Accomplishments and Progress (cont.)

- Turbine Runner Testing
  - Reynolds Sensitivity Sweep Results
    - Reynolds number based on blade chord and relative velocity at tip
    - Hydrodynamic performance insensitive to changes in Reynolds number

Dimensional Test Conditions

Variable	Full Scale	CFD	Tunnel Test
Rotor Pitch (◦)	19	19	19
IGV Pitch (◦)	63	63	63
D (m)	1.155	0.887	0.887
N (rpm)	375	350	182
Q (m^3/s)	6.03	2.47	1.5
Reynolds Number	11,000,00	5,900,000	1,500,000

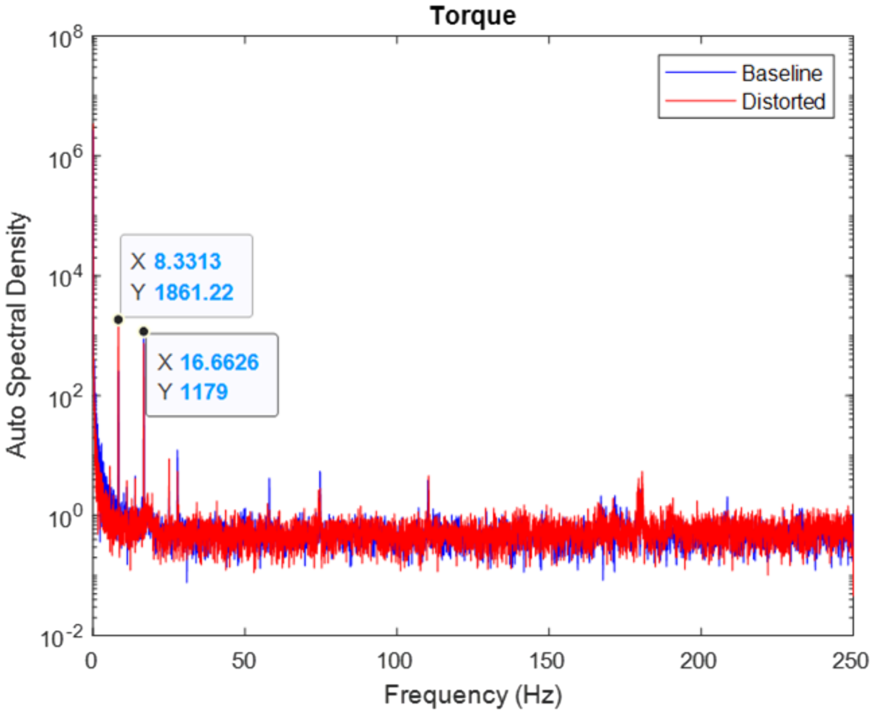


Hydrodynamic efficiency vs. Capacity Coefficient

Performance: Accomplishments and Progress (cont.)

- Turbine Runner Testing
  - Condition Based Maintenance Test Results
    - Generating simulated fault condition to evaluate if sensors in turbine system can be used to detect changes in operation
    - Would allow monitoring of system health
    - Fault condition simulated by removing two Inlet Guide Vanes

IGV blades removed to simulate a fault condition



- Overall spectra of the torque sensor timeseries indicating no instability
- Minor differences in frequencies, but not significant enough to be indicators for system health monitoring
- Shows that the composite runner system is a robust system hydrodynamically

Summary & Conclusions

- Materials selected in Phase I proven in real-world simulated testing
- Composite runner turbine blades successfully fabricated using VARTM process
- Mechanical laboratory testing showed good correlation between predicted FEA performance and actual blade performance
- Scaled Voith Bulb hydroturbine successfully designed, fabricated, and deployed in PSU/ARL water tunnel
- Composite runner set successfully tested under simulated hydroturbine operational conditions
  - Hydrodynamic performance similar to stainless steel runners
  - Surface roughness and tolerances for the composite runner blades did not have a significant impact on performance parameters
  - No indication of cavitation was experienced, audibly or after visual inspection of the blades, indicating that the anti-cavitation coating performed as expected
- Proved that advanced manufacturing methods and materials used in the composite turbine blades are viable candidates for use in hydroturbines

Q&A