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Applied Research Laboratory

Marine Renewable Energy Capabilities

ARL Penn State

October 2008

The Applied Research Laboratory (ARL) at Penn State, one of five Navy designated University Affiliated Research Centers (UARC), has been conducting basic and applied research for over 63 years.

Traditional Naval Research Capabilities Are a National Asset for the DOE Marine Renewable Energy Initiative

Undersea expertise and unique testing capabilities that have been developed over the past 63 years under DOD sponsorship are well suited for use in the DOE Marine Renewable Energy Initiative. This pamphlet has been put together specifically to provide an insight into many of the traditional areas of technical expertise at the ***Applied Research Laboratory*** at Penn State as they relate to this emerging area of renewable energy research in the US.

In the hills of central Pennsylvania exists the ***Applied Research Laboratory***, a U.S. Navy designated University Affiliated Research Center whose primary purpose since 1945 has been to supply the Navy and other DOD agencies with basic and applied research in a host of undersea technology areas. As a part of **The Pennsylvania State University's Defense-Related Research Units**, ARL serves as a center of excellence in undersea hydrodynamics, acoustics, advanced marine materials, energy systems, manufacturing methods, guidance and control, and information management.

In addition to a technical staff of over 1100 scientists, engineers and students, ARL is home to many unique experimental facilities for design and prototype development of undersea technologies. The flagship research testing facility is the **Garfield Thomas Water Tunnel (GTWT),** a high-speed, closed-loop water tunnel used for research of cavitation, acoustics, and advanced rotating machinery design. Other smaller, specialized facilities also exist to support the core technology interests.

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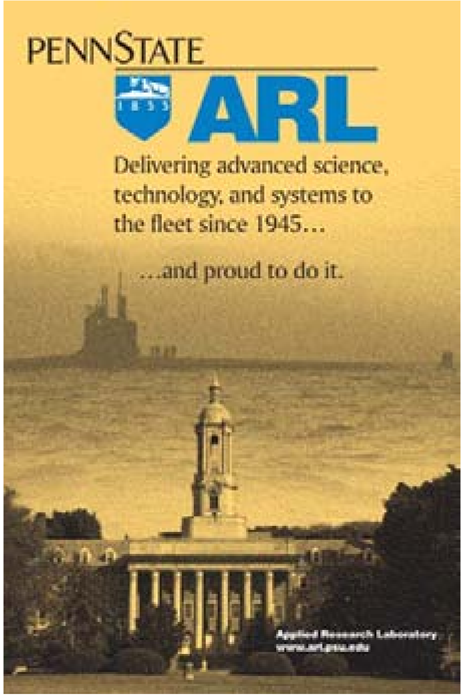
Construction of the Garfield Thomas Water Tunnel - 1949

We Are Penn State!



Penn State University, currently one of the top universities in annual research funding, was established in 1855 as a land grant school and currently enrolls more than 80,000 students (~11,000 advanced degree). The Applied Research Laboratory (ARL) at Penn State was established in 1945 to advance the U.S. Navy’s technology base through research and development. As a Research Unit of Penn State, ARL is the largest single contributor to Penn State’s research programs. ARL research faculty teach and mentor Penn State students, are active members of the graduate faculty of several academic departments, and interact and collaborate with academic faculty members on both ARL and Penn State initiated research programs.

In addition, ARL makes use of over 200,000 square feet of engineering and testing facilities dedicated to hydrodynamic applications; advanced rotating machinery, water tunnel testing, acoustics, simulation, manufacturing technologies (including marine composite material testing and fabrication), system modeling, and information visualization.

Energy

Penn State is a regional leader in research and implementation of energy -related technologies, ranging from energy conservation in new campus construction, the Penn State Institute for Energy and the Environment, the Navy Center for Sustainability, fuel cell and biomass research along with collegiate construction competitions for solar building (Solar Decathlon ’07 & ‘09), and hybrid vehicle prototypes (Challenge X, EcoCAR). Though the university does not currently host a Marine Renewable Energy (MRE) program, ARL’s applied research focus and expertise in marine-based energy systems makes it an ideal environment for accelerated design, development and commercialization of MRE systems. While ARL’s traditional products have concentrated more on transfer of energy to water or fluids, the tools, methods, test facilities, and technical expertise are completely transferable to the developing marine renewable energy industry.

… ARL’s applied research focus and expertise in marine based energy systems makes it an ideal environment for accelerated design, development and commercialization of MRE systems.

To aid in the development of a comprehensive marine renewable energy initiative that concentrates on ocean, river, and tidal devices, ARL Penn State has joined forces with a primarily undergraduate institution with expertise in river flows and sediment transfer dynamics. Collaboration of ARL Penn State and the **College of Engineering at Bucknell University** provides a unique capability with access to their faculty and testing facilities and provides potential field testing through their Susquehanna River Initiative (SRI).

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Core Capabilities

Hydrodynamic Design & Analysis
Unique for a naval propulsion R&D center, ARL employs a turbomachinery approach to the design and analysis of propulsion and pumping equipment. This is a result of Penn State's land grant mission and the long standing relationship with industrial equipment manufacturers such as GE (jet engines and steam turbines), Westinghouse (steam turbines and pumps), Ingersoll-Rand (Cameron Pump), Voith-Siemens (hydro-turbines and pumps), and government labs such as NASA (aerospace and air breathing propulsion).

The ARL turbomachinery design process integrates a traditional hydrodynamic design methodology with in-house state-of-the-art computational fluid dynamics (CFD) analysis and validation testing within a comprehensive and physics-based process. This process has been refined and validated over the years by many programs and successful applications.

The ARL turbomachinery design process integrates a traditional hydrodynamic design methodology with in-house state-of-the-art computational fluid dynamics (CFD).

Geometric Scaling ARL has extensive experience with scaling hydrodynamic forces and moments based on its extensive experience in naval propulsion and pump R&D. Although hydrodynamic scaling methodologies and practices vary between industries, the fundamental procedures rely on the principles of dynamic similitude (*i.e.*, non-dimensional analysis) for first order scaling. Higher level scaling requires an understanding of the impact of viscosity (*i.e.*, Reynolds number) and gravity (Froude number). Legacy engineering models are employed as necessary and complimented with computational modeling when needed. In all cases, consistency in approach and method is the goal.

High Reynolds Number Pump Test Facility
Installed in the GTWT Test Section

ARL is recognized as a leader in cavitation inception testing and scaling. While it is acknowledged that cavitation will not always be a concern in marine renewable energy systems, the scaling methodologies employed are relevant. The traditional surface cavitation forms are readily handled with traditional, well-validated models. The more challenging vortex cavitation forms have been the focus of extensive research efforts which have yielded viable models. This is especially beneficial to the projection of full-scale cavitation performance, since vortex cavitation may dominate full-scale performance of a marine turbomachine. This is analogous to the hydro-turbine draft tube cavitation which is Froude number dependent and yields large full-scale unsteady forces. In both cases, analysis of the model-scale data and pragmatic application of physics-based CFD tools is required to predict full-scale characteristics.

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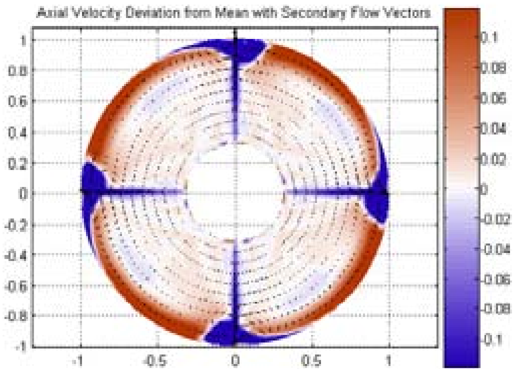
Vibration and Noise

A critical part of ARL's turbomachinery design process for the US Navy involves providing design and analysis capabilities such that the turbomachinery system will produce minimal vibration and resultant radiated noise. In most, if not all real world applications, a renewable energy device will be exposed to a spatially and temporally varying, turbulent flow field. This turbulent inflow produces unsteady loading on the kinetic energy extracting components of a MRE device translating into induced vibration and noise. Some recent mechanical failures of both wind and marine RE devices can be linked to flow induced unsteady loading on the turbines. From a life-cycle perspective, it will be important to design renewable energy systems in which the unsteady forces on the turbine blades and shafting system (due to incoming turbulent flow) are minimized. ARL's in-house design and analysis tools can be used to analyze turbine blade shapes and provide a design that will minimize unsteady forces transmitted down the shaft. The figure on the right shows a spatial decomposition of the unsteady velocity vector field behind four stationary struts used to calculate unsteady lift of a notional downstream turbine. Such flow fields can be obtained either experimentally in the GTWT or computationally using CFD. Data such as that shown on the right allow the turbine blade design to be optimized to minimize unsteady loads for a given operating environment.



Axial velocity vector field behind struts

Test Facilities

A sample of the available ARL test facilities include:

- Three high Reynolds number water tunnel facilities
- A unique low Reynolds number, high speed (<10 m/s) glycerin tunnel with a 284.4 mm diameter test section
- A small open return wind tunnel
- High Reynolds number pump loop facility
- Hydrodynamic anechoic/reverb tank
- Computational Mechanics – over 300 processors across multiple in-house clusters

ARL's in-house design and analysis tools can be used to analyze turbine blade shapes and provide a design which will minimize unsteady forces transmitted down the shaft.

The hydrodynamic anechoic/reverb test tank is 7.9 meters long by 5.3 meters wide by 5.5 meters deep and structurally isolated for hydrodynamic acoustic tests. The tank has three 0.5 x 0.5 meter underwater view ports. Two mechanical cranes on rail systems can be used to rig transducers and arrays to extension pedestals and fixed placement carts for accurate positioning and synchro-controlled measurement of azimuth and depth. Water-tight housings exist to allow flow field mapping around the model using a variety of existing instrumentation (PIV, LDV, video) within the tank.

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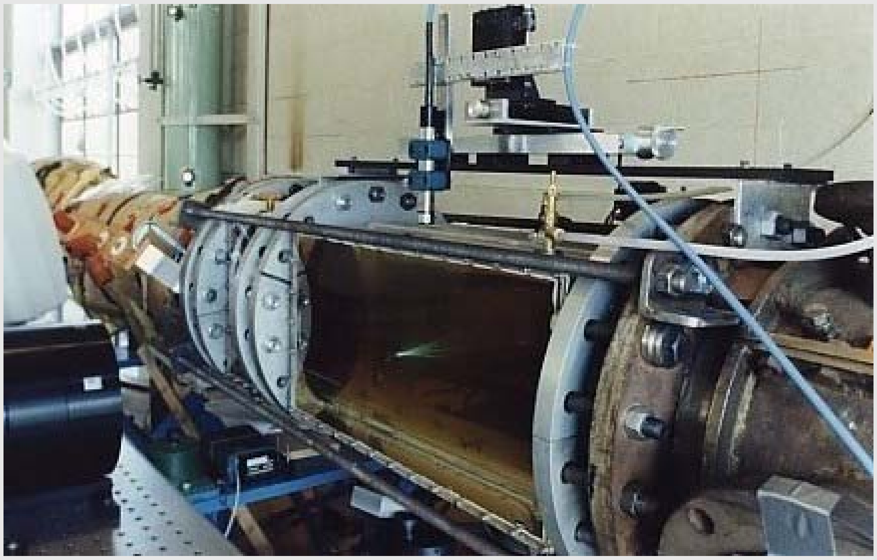
GARFIELD THOMAS WATER TUNNEL – 48-INCH DIAMETER WATER TUNNEL	
Description	Closed Circuit, Closed Jet
Drive System	4-Blade Adjustable Pitch Impeller
Motor Power	2,000 hp Variable Speed (1,491 kW)
Working Section Size and Max Velocity	1.2 m diameter x 4.3 m long (48” x 168”) 17 m/s (55 ft/sec)
Max / Min Absolute Pressure	20.7 to 413.7 kPa (3 to 60 psia)
Cavitation No. Range	> 0.1 depending on velocity and advance ratio
Instrumentation	Propeller dynamometers, Pitot probes, laser based diagnostics, pressure sensors, hydrophones, force balances, accelerometers, acoustic arrays
Torque and Thrust Dynamometers	Model internal mounts, 150 hp limit (111.85 kW)
Model Size Range	76.2 mm to 635 mm (3 to 25 inches)
Tests Performed	Forces, flow field surveys, pressure distributions, cavitation performance, noise measurements, vibrations, unsteady forces, flow visualizations, torque, thrust, moments
Other Remarks	Turbulence level is 0.1 percent measured in the test section. Air content can be controlled as low as 1 ppm per mole.
GTWT test section is equipped with extensive visual access for cavitation viewing and advanced laser anemometry measurements	

12-INCH DIAMETER WATER TUNNEL

Description	Closed Circuit, Closed Jet
Drive System	Mixed Flow Peerless Pump
Motor Power	150 hp Variable Speed (111.8 kW)
Working Section Size and Max Velocity	Circular Test Section – 305mm dia x 762 mm (12” dia x 30”) Rectangular Test Section – 508 mm x 114 mm x 762 mm (20” x 4.5” x 30”) 21 m/s (69 ft/sec)
Max / Min Absolute Pressure	20.7 to 413.7 kPa (3 to 60 psia)
Cavitation No. Range	> 0.1 depending on velocity and advance ratio
Instrumentation	Pitot probes, lasers, pressure sensors, hydrophones, miniature force balances, accelerometers, acoustic arrays
Model Size Range	101 mm max (4 inches)
Tests Performed	Steady state and time dependent force and pressure measurements on unpowered models; noise measurements on cavitating bodies; 3-dimensional flow problems with circular test section; 2-dimensional problems with rectangular test section.
Other Remarks	Turbulence level is 0.1 percent measured in the test section. Air content can be controlled as low as 1 ppm per mole.
12” diameter water tunnel with circular test section installed	

BOUNDARY LAYER RESEARCH TUNNEL (GLYCERIN)	
Description	Closed Circuit, Closed Jet
Drive System	Gould Centrifugal Pump
Motor Power	100 hp Constant Speed (74.6 kW)
Working Section Size and Max Velocity	Circular Test Section – 285 mm diameter (11.2 inches) < 10 m/s (32.8 ft/sec)
Max / Min Absolute Pressure	atmosphere
Reynolds No. Range	4,000 – 15,000
Instrumentation	Laser anemometry, pressure sensors, hydrophones, miniature force balances, accelerometers, acoustic arrays
Tests Performed	This facility models the turbulent flow of fluids next to a wall at a scale large enough to permit detailed measurement of the flow structure in the viscous sublayer. Tests have been performed in basic shear layer turbulence structure, CFD validation and fluid/structures interaction.
Other Remarks	Specifically designed for research in the viscous sublayer; wide Reynolds numbers range for turbulent boundary layer research; 20 micrometer filter and heat exchanger; internal surface of metal test section honed to 0.41 rms micrometer finish; clear acrylic test section for laser anemometry.
Boundary Layer Research Facility – acrylic test section, working fluid is glycerin	

REVERBERANT TANK	
Description	Anechoic / Reverberant Test Tank
Dimensions	7.9 m x 5.3 m x 5.5 m deep (26 x 17 x 18 feet)
Characteristics	Structurally isolated for hydrodynamic acoustics testing. Lined with an absorber on four sides and bottom with three 0.5x0.5 meter underwater viewing ports.
Max / Min Absolute Pressure	Ambient
Instrumentation	Mechanical oscillation of a small-scale test unit within the tank provides simulation of an oscillating flow pattern to simulate wave or tidal flow excitation. Extensive use of non-intrusive instrumentation is available including laser Doppler anemometry, particle image velocimetry, and laser vibrometry, modal testing, and material testing.
Model Size Range	Hardware up to 6 ft
Tests Performed	Structural dynamic testing where fluid loading characteristics are critical. Vibratory characterization of metal and non-metal structures. Damping and admittance properties of large-scale structures.
Laser vibrometry measurements being performed through reverberant tank facility underwater windows.	

BUCKNELL SEDIMENTATION FLUME	
Description	High-speed, open channel hydraulic flume
Dimensions	32 ft x 4 ft x 2 ft
Working Section Size and Max Velocity	2.8 m/s (9 ft/sec)
Max / Min Absolute Pressure	atmosphere
Instrumentation	The flume has been instrumented with an automated 3axis Positioning System with traversing capability for the entire length, width and height of the flume with a resolution of 0.001 inch. This positioning system can hold probes at any location within the flume to make point measurements for flow parameters, such as pressure and velocity to properly characterize a flow field. The flume has an Acoustic Doppler Velocimeter (ADV) a non-intrusive instrument which provides 3-axis velocity measurements (range is 2.5 m/s) by using acoustic sensing techniques to measure flow in a remote sampling volume (0.25 cm^3). Glass-sided walls facilitate viewing and use of optical techniques for measurements.
Tests Performed	The flume can also be converted to a sediment flume where the bottom is filled with a natural sediment material to perform small-scale studies of erosion, aggradation and scouring processes. Mapping of the bottom topography due to changes in flow patterns in and around solid structures can be re-constructed for further analysis.
Photos of flume facility	
New facility under construction	The geology department at Bucknell University is constructing (completion March 2009) a sediment-recirculating flume, 40-foot long by 10-foot wide, for the exploration of fluid dynamics impact on sediment transport/deposition and river morphology impact. The facility will host research in mitigation of sediment scour, erosion and transport. A sophisticated laser instrumentation system to map the topography of the river bed has also been approved for purchase to be tested and used in the sediment flume.

Field Testing

NUWC Keyport - A longstanding relationship has existed between ARL Penn State and the Naval Undersea Warfare Center (NUWC) in Keyport, WA for over 30 years. ARL maintains a permanent workforce, office, and lab space at this Navy facility. The extensive field test capabilities at NUWC-Keyport allow for a realistic end-to-end product test and evaluation of large-scale MRE technologies. Results of this testing can be used for final product development and commercialization.

Field Testing on the Susquehanna River

The ARL-Bucknell collaboration provides potential for field testing of smaller devices for rivers or streams through the Susquehanna River Initiative (SRI).

Bucknell University – The ARL-Bucknell collaboration provides potential for field-testing of smaller devices for rivers or streams through the Susquehanna River Initiative (SRI). This initiative is a major program sponsored by the Bucknell leadership role in long-term studies of a University Environmental Center (BUEC) to integrate research, teaching and outreach focused on the Susquehanna River: "…The largest non-navigable river in North America, the Susquehanna is the major source of fresh water to the continent's largest estuary, the Chesapeake Bay. The health of the bay ecosystem is intimately linked to the land use and natural hydrogeomorphic processes upstream in the watershed. Bucknell is ideally situated on the banks of the river. Through the SRI, Bucknell is developing a world-class research program in watershed science and humanities and a unique interdisciplinary teaching curriculum that emphasizes experiential learning. Major activities currently under development are firmly grounded in research and teaching, but also include significant outreach and interaction with groups and programs beyond Bucknell, such as an association with the Susquehanna River Heartland Coalition for Environmental Studies (SRHCES)…." (www.departments.bucknell.edu/environmental_center/inside/).

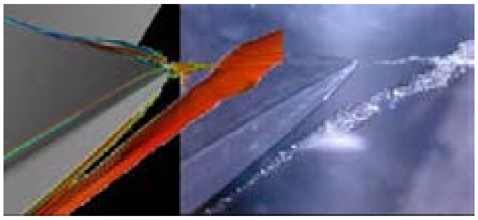
Environmental Impact Testing – In addition to the potential field testing capabilities on the Susquehanna River, the ARL-Bucknell collaboration provides expertise and experimental capabilities to assess the Environmental Impact from MRE device employment, with particular emphasis on sediment transport and the suspension of sediment and buried contaminants.

Field tests conducted at the Naval Undersea Warfare Center (NUWC) in Keyport Washington – Dabob Bay.

Computational Capabilities

Mature, validated computational tools are available for preliminary design through final prototype testing of MRE devices and sites. Available flow solvers are a mix of in-house, open-source, commercial, and community codes for engineering and numerical weather prediction. Capabilities exist for modeling single and multi-phase compressible and incompressible flows. Tools are equipped with modern CFD technologies providing parallel computing, overset gridding, steady and unsteady Reynolds Averaged Navier-Stokes (RANS) solvers, Large Eddy Simulation (LES), 6 degree of freedom (DOF) dynamics, high-order discretization practices, and high resolution grid motion/deformation capabilities. CFD engineers are equipped with high performance computers for grid generation and post-processing of large datasets. ARL supports in-house clusters for high priority design work with over 3 million processor hours/year capacity (across 300 processors). Further off-site HPCMO and NASA project allocations may be used as needed.

Blade Cavitation Prediction and Experiment



Additional Capabilities

This pamphlet provides a quick look into some of the capabilities and facilities of the Applied Research Laboratory at Penn State and our partner Bucknell University as they apply to marine renewable energy initiatives. ARL's capabilities list is not intended to be exhaustive or complete since there are many highly qualified researchers and scientists at Penn State and Bucknell, as well as Professors from the HBCU's that ARL collaborate with (such as Tennessee State University), that are ready and willing to lend their expertise to the very large problem set at hand. Some of the other areas which can be tapped and brought to bear for MRE problems include:

- Ocean Environments
- Wildlife and Fisheries Science
- Marine Mammal Biology
- Large Scale Manufacturing
- Marine Composites
- Gear & Drive Train Technology
- Hydrodynamics
- Cavitation
- Turbomachinery
- Automation & Intelligent Control
- Remote Monitoring
- Conditioned Based Maintenance
- Information Technology
- Electrical & Civil Engineering
- Mech & Aerospace Engineering

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