



Materials Considerations for Marine & Hydrokinetic Energy Technology

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Sponsored by the US Department of Energy, Office of Energy Efficiency and Renewable Energy (US DOE-EERE) Water Power Technologies Office

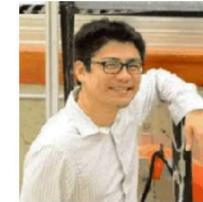


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Team Introductions:

■ Sandia National Laboratories

- Bernadette A. Hernandez-Sanchez: (PI)
Materials Chemistry
- Budi Gunawan-Loads & FBG Sensors



■ Pacific Northwest National Laboratory

- George Bonhoyo (WSU): Biofouling



Washington State
University

■ National Renewable Energy Laboratory

- Scott Hughes: Substructure Testing



■ Montana State University

- David Miller:
Composite Performance



■ Florida Atlantic University

- Francisco Presuel-Moreno: Corrosion



Project Overview

Marine and Hydrokinetics Advanced Materials Program: support the

MHK industry through applied research and guidance on Materials & Coatings to enable viability, lower the cost of energy (COE), **\$0.12–\$0.15 per kilowatt-hour (kWh) by 2030**, and accelerate commercialization

The Challenge: Proper structural/component materials and coatings are critical to reducing engineering barriers, COE, and commercialization time

- **Structure Design & Component:** (LOADS! uncertainty in composite/design)
- **Environmental Exposure Issues**
- **Cost (Manufacture, O&M, Reliability)**
- **Safety & Certification**



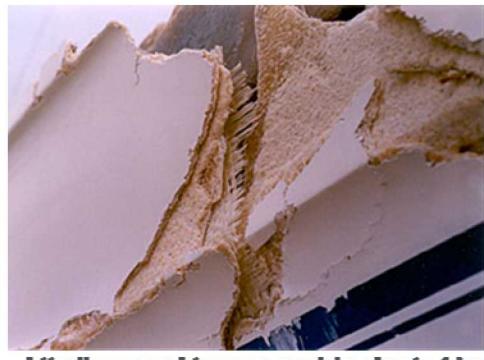
Current Program Objective: **Helping MHK industry reduce uncertainty in using composites in their designs.**

- Direction taken from 2015 Workshop on Composite Needs for MHK
- Past efforts involved determining materials needs for industry, examining coatings for biofouling, and examining marine effects on wind based composites.

Helping the MHK industry with materials & protective coatings challenges



Courtesy of Resolute Marine Energy



<http://www.yachtsurvey.com/glassboats-1.jpg>

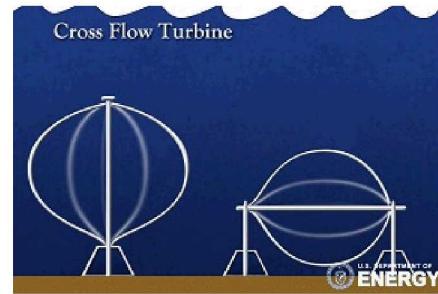
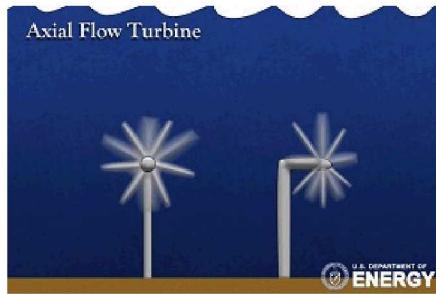
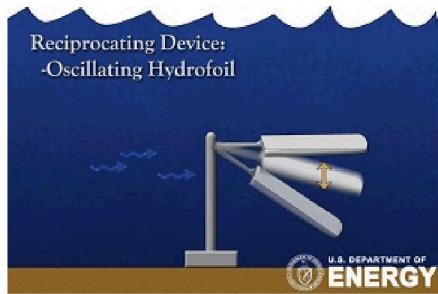
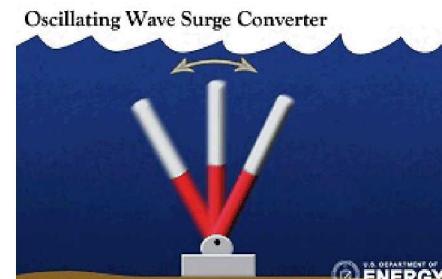
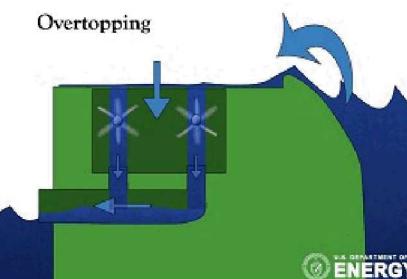
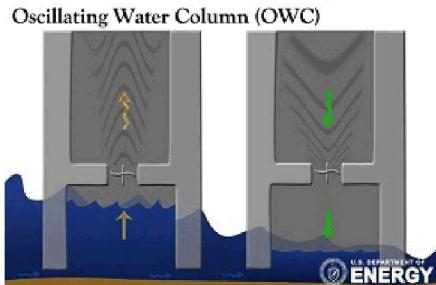
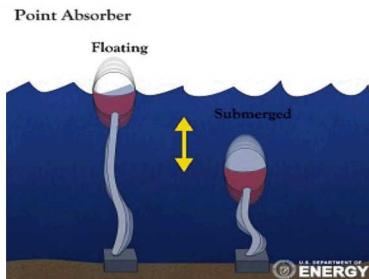


<http://www.racerocks.ca/>



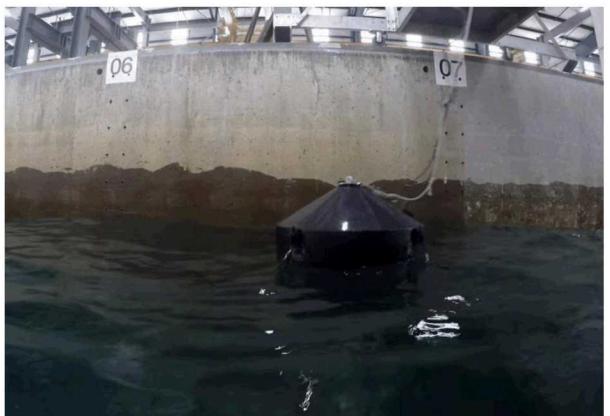
ICIT & EMEC
<http://tidalenergystoday.com/2016/01/12/icit-emec-study-biofouling-of-marine-energy-technologies/>

Why composites right now?



- Areas of concern vary by design: metals, hydraulic fluids, polymers, cement, magnetic, coatings, composites
- Composites: Reinforced rubbers, reinforced concrete, fiber reinforced plastics
- Reference Models (SNL, NREL); Wave Energy Scotland Structural Loads and Materials Landscape Study, 2011 Carbon Trust report indicate the structure costs can be impacted by using light weight and non-corroding materials.

Examples of Some MHK Designs Exploring Composite Materials (listed in alphabetical order)



AquaHarmonics



Columbia Power Technologies



Lockheed Martin-OTEC
Cold Water Pipe



Ocean Renewable Power Company



Resolute Marine Energy



Verdant Power

Environmental effects and materials must be considered in structural loading.



IEC TS 62600 -2 ED2 (2018)
Marine energy - Wave, tidal
and other water current
converters - Part 2: Design
requirements for marine
energy systems



Structural Forces and Stresses for
Wave Energy Devices

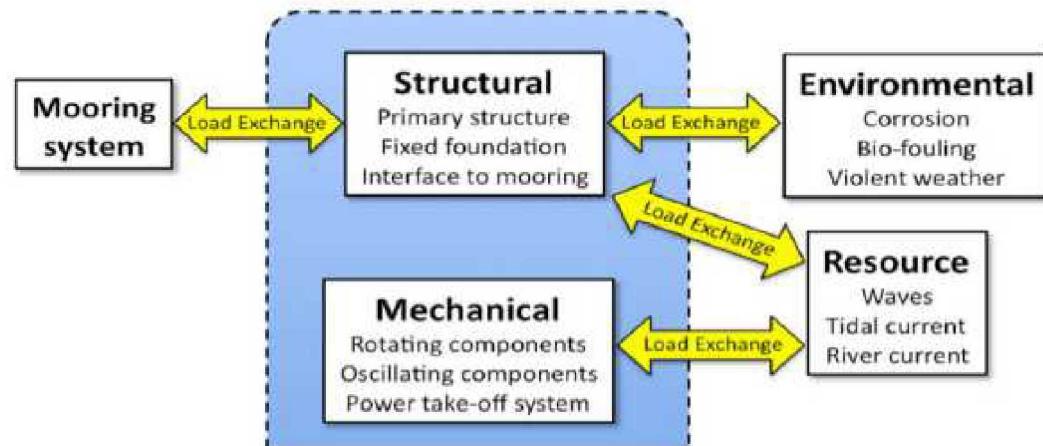
Final Report

WES.0002.01 Forces and Stresses



ARUP

Structural forces and stresses
for wave energy devices.
Wave Energy Scotland Report
(2016)



Load exchanges covered under
IEC TS 62600 -2 ED2 (2018)

Design load

$$F_d = \gamma_f F_k$$

where:

- F_d is the design value for loads acting on the MEC for the given design load case
- γ_f is the partial safety factor for loads
- F_k is the characteristic value for the load

Design materials

$$f_d = \frac{f_k}{\gamma_m}$$

where:

- f_d is the design values for materials
- γ_m is the partial safety factors for materials
- f_k is the characteristic values of material properties

Ensure material's strength exceed design loads

Materials can impact the following:

- Structure costs
- Better designs and manufacture
- Accelerating manufacturing or Advanced Manufacturing Strategies
- Testing of Novel Materials or Materials from Marine Industries to Reduce Risk
- Open water testing on materials for validation
- Reliability and Survivability
- Operation & Maintenance
- Certification & Safety

Our current program's goal is to address barriers & uncertainty in using composite materials for MHK.



Material Design Tools for Marine and Hydrokinetic Composite Structures

Objective: Helping MHK industry reduce uncertainty in using composites in their designs

- Providing an *industry approved* U.S. DOE MHK Composite Materials & Structures Database (*open resource*): <http://energy.sandia.gov/energy/renewable-energy/water-power/technology-development/advanced-materials/mhk-materials-database/>
- Mitigating composite biofouling/environmental effects & metal-carbon fiber interconnect corrosion in saltwater
- Examining MHK load challenges on composite material & substructure performance to improve design

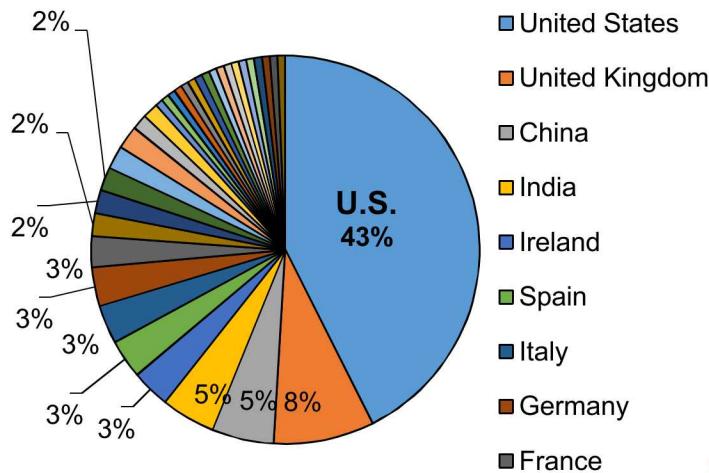


The MHK Composite Materials & Structures Database was born from discovery in wind energy.

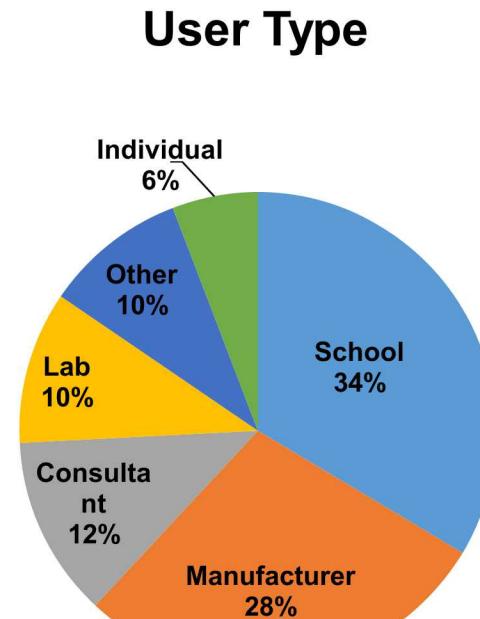
U.S. DOE MHK Composite Materials & Structures Database:

Benefits: Open Source, Industry Advised, Backed with Publications.

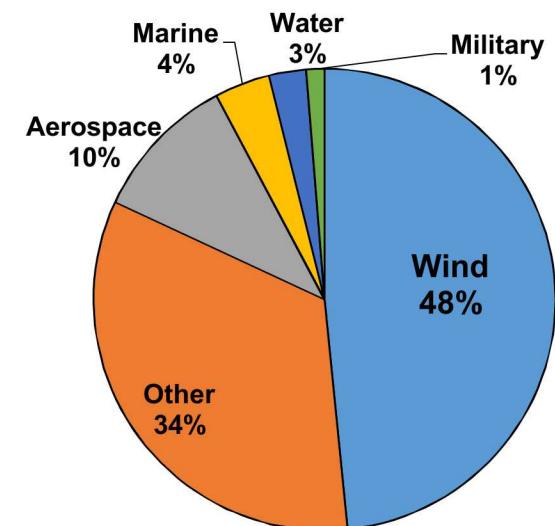
Country



User Type

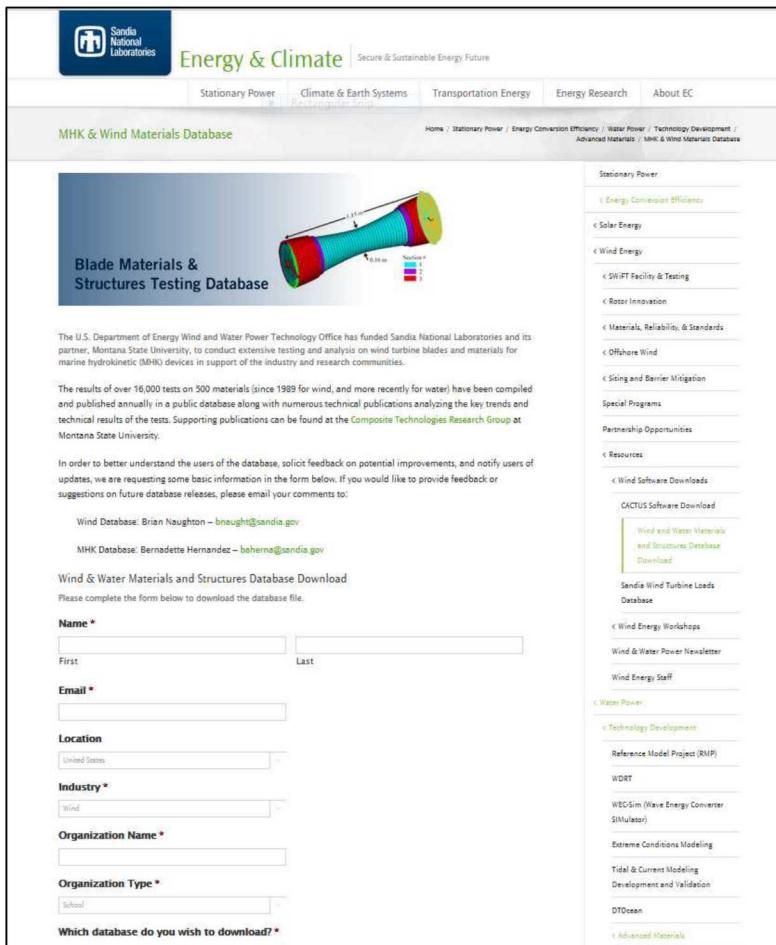


Institution



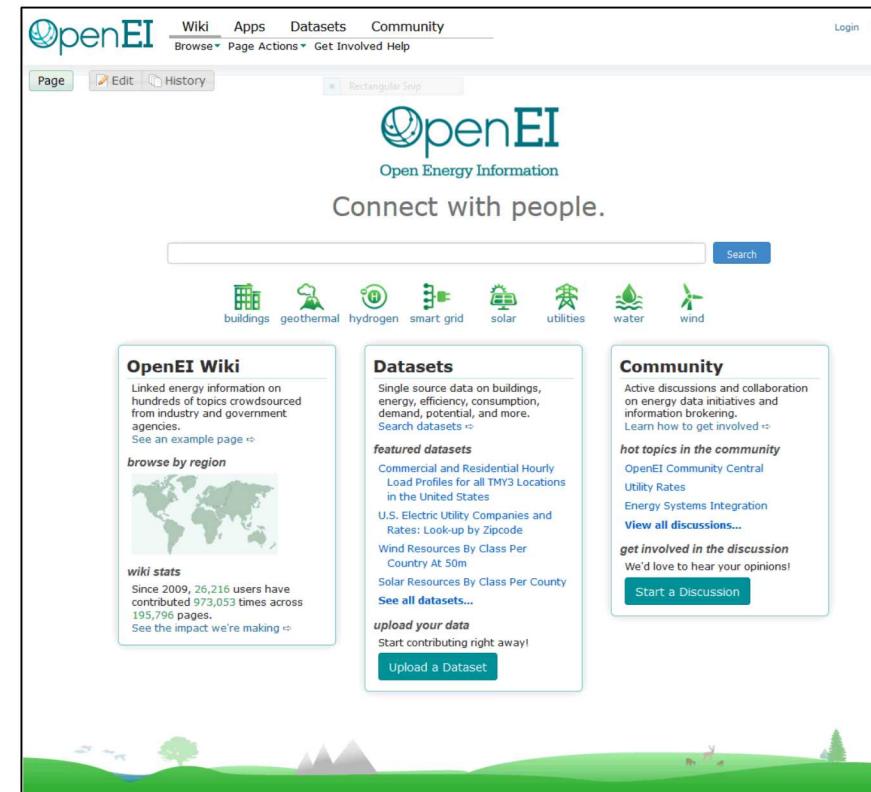
- <http://energy.sandia.gov/energy/renewable-energy/water-power/technology-development/advanced-materials/mhk-materials-database/>

Database can be found in 2 locations online and is free for users to download.



The screenshot shows the Energy & Climate website under the "MHK & Wind Materials Database" section. The main content area features a 3D rendering of a wind turbine blade. The left sidebar contains a form for downloading the database, with fields for Name, Email, Location, Industry, Organization Name, Organization Type, and a question about which database to download. The right sidebar lists various links related to stationary power, wind energy, and water power.

<http://energy.sandia.gov/energy/renewable-energy/water-power/technology-development/advanced-materials/mhk-materials-database/>



The screenshot shows the OpenEI website. The header includes links for Wiki, Apps, Datasets, and Community. The main content area features the OpenEI logo and a call to action: "Connect with people." Below this are sections for "OpenEI Wiki", "Datasets", and "Community". The "Datasets" section includes a world map and a "wiki stats" box. The "Community" section has a "hot topics in the community" list and a "get involved in the discussion" section.

- Both the wind and water icons take you to webpages that house the link.
- Under Water Power Database and Tools

Databases



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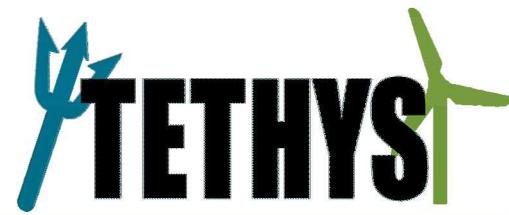
Wind & Water Materials and Structures

The screenshot shows the Sandia National Laboratories Energy & Climate website. The main navigation bar includes 'Stationary Power', 'Climate & Earth Systems', 'Transportation Energy', 'Energy Research', and 'About EC'. Below this, a sub-navigation bar for 'MHK & Wind Materials Database' includes 'Home', 'Stationary Power', 'Energy Conversion Efficiency', 'Water Power', 'Technology Development', 'Advanced Materials', and 'MHK & Wind Materials Database'. The main content area features a 3D rendering of a wind turbine blade with dimensions: 1.15 m (length) and 0.16 m (width). The text 'Blade Materials & Structures Testing Database' is displayed. A detailed description follows, mentioning the U.S. Department of Energy Wind and Water Power Technology Office's funding of Sandia National Laboratories and its partner, Montana State University, to conduct extensive testing and analysis on wind turbine blades and materials for marine hydrokinetic (MHK) devices. It notes over 16,000 tests on 500 materials since 1989, published annually in a public database with technical publications. A feedback form is provided for users. Contact information for Wind Database (Brian Naughton) and MHK Database (Bernadette Hernandez) is listed. A 'Wind & Water Materials and Structures Database Download' section is also present.

<http://energy.sandia.gov/energy/renewable-energy/water-power/technology-development/advanced-materials/mhk-materials-database/>

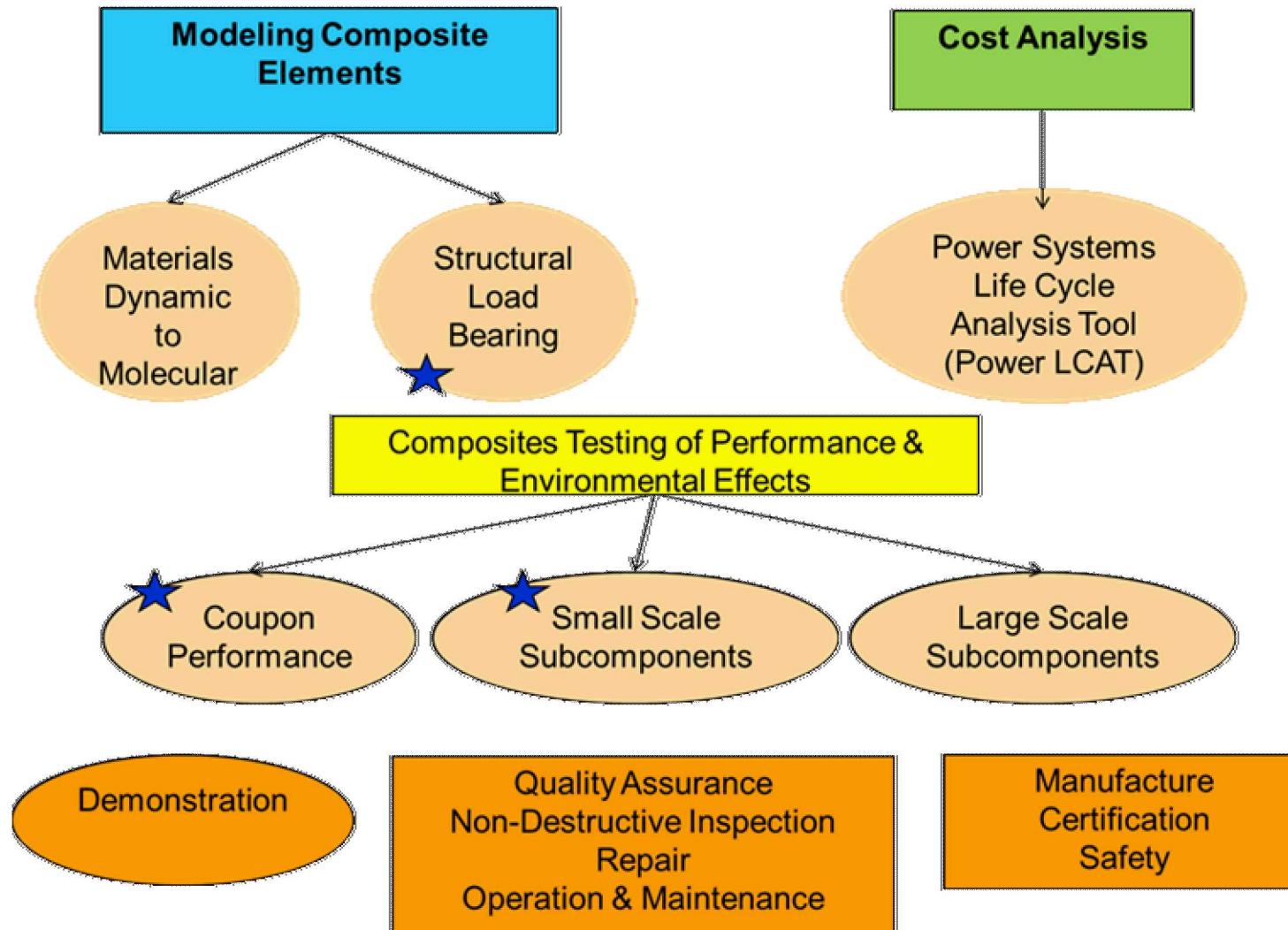


https://openei.org/wiki/Main_Page



<https://tethys.pnnl.gov/>

Our study is the initiation of research for bigger vision to support composite development.



Current Activities and Future Directions

FY17



Salt Water Effects on
Composite Performance
Testing

Coupons provided by:

Composites Engineering Research Lab, Composites Technology Development, Hygrateck, Janicki, Industries, Polyone, Ocean Renewable Power Company, Verdant

Biofouling &
Environmental Effects on
Composites



FY18

Metal – Carbon Fiber
Composite Interconnects
in Seawater

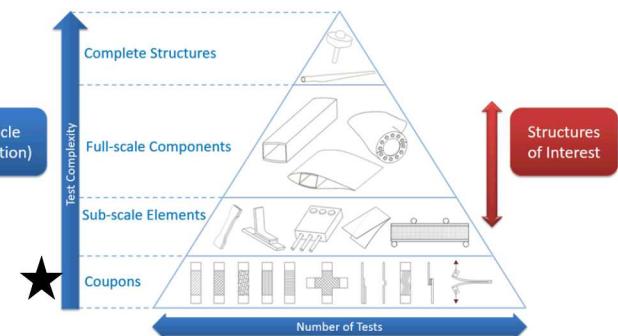
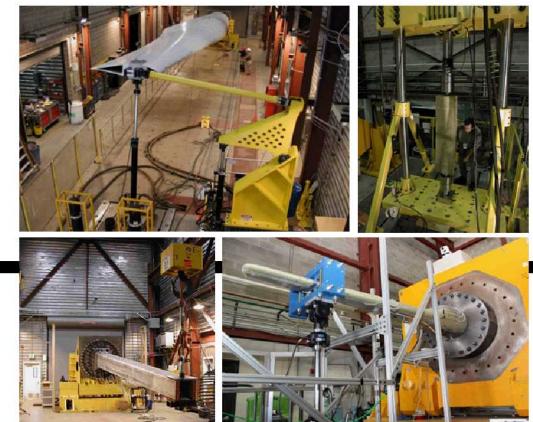


**Industry directed sub scale
elements & joined coupon
fabrication/testing**
(Artificial & Actual Seawater)



FY19

**Industry directed full scale
subcomponent testing**
(Artificial & Actual Seawater)

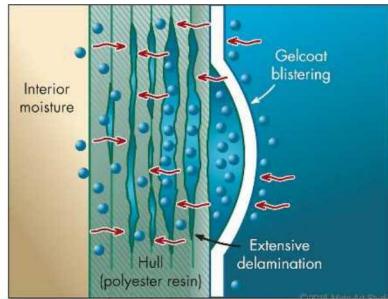


MHK Material Needs

Engineering designs of MHK devices have difficult, although not unique, materials challenges



They must be strong, stiff and yet lightweight



They must resist environment degradation

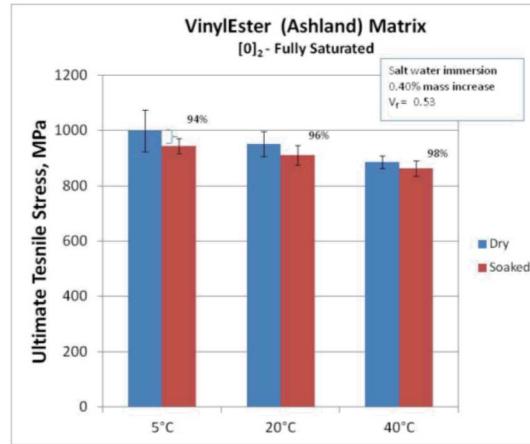
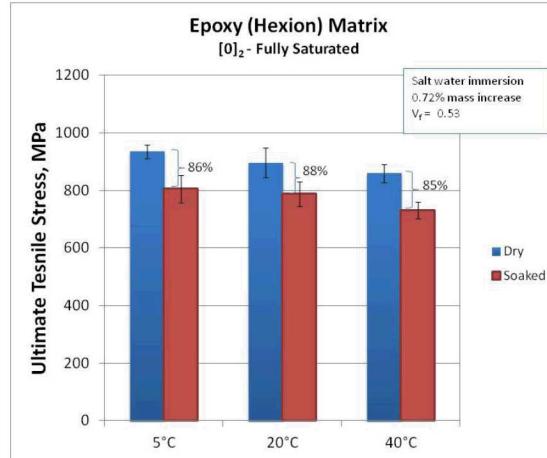
They must be durable



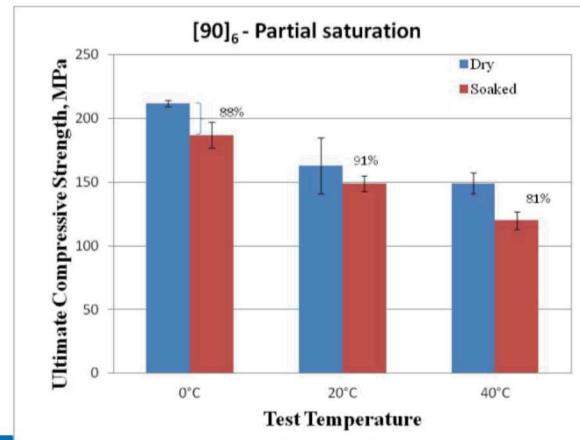
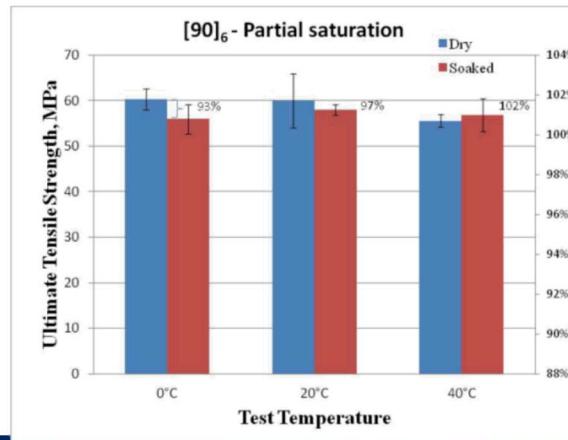
They must be inexpensive and easy to integrate into manufacturing



Effects of soaking and temperature



Fully Saturated a) epoxy Tensile sample with 0.72 % Wt. Gain, $V_f = 0.53$ b) vinyl-ester Tensile sample with 0.40 % Wt. Gain, $V_f = 0.53$, Cured at 80 °C and soaked at 50°C.



2012 AIAA SDM Wind Energy Session

Industry-supplied coupon investigation

- Current program results
- Tensile static and fatigue, $R = 0.1$, testing on 33 different laminates, from five suppliers
- Testing was performed on unconditioned and simulated seawater conditioned coupons of each laminate
- The static and fatigue tests on the 33 different laminate configurations required over 175 machine days (4148 hours) of continuous testing time after 90+ days of moisture conditioning.
- Thermoset and thermoplastic coupon sets
- Acoustic emission data collected to investigate damage propagation in both dry and saturated coupons

Thermoplastics

MSU	# of			
LABEL	plates	Fiber	Resin	Layup
P1	1	E-Glass	PP	0/90/0/90/0/90
P4	1	E-Glass	PA6	0/90/0/90/0/90
P5	1	E-Glass	PA11	0/90/0/90/0/90
P6	1	E-Glass	PET	0/90/0/90/0/90
P9	1	E-Glass	PETG	0/90/0/90/0/90
P11	1	E-Glass	HDPE	0/90/0/90/0/90
P13	1	E-Glass	PP	0/90/0/90/0/90
P2	1	E-Glass	PP	[0]6
P3	1	E-Glass	PA6	[0]6
P7	1	E-Glass	PET	[0]6
P8	1	E-Glass	PETG	[0]6
P10	1	E-Glass	HDPE	[0]6
P12	1	E-Glass	PP	[0]6
P14	1	E-Glass	PA11	[0]6

Thermosets

MSU LABEL	# of plates	Fiber	Resin	Layup
J6	1	Carbon	Applied Poleramic SC18	[0/45/0/45/0/45/0/45]
J7	1	Carbon	Applied Poleramic SC18	[0/0/0/0]
J8	1	Carbon	Derakane 470 HT-400 VE	[0/45/0/45/0/45/0/45]
J5	2	E-Glass	Applied Poleramic SC18	[0/45/0/45/0/45/0/45]
J3	2	E-Glass	Applied Poleramic SC18	[0/0/0/0]
J1	1	E-Glass	Eastman Copolyester 5011, PETG	[0/0/0/0]
J4	1	E-Glass	Derakane 470 HT-400 VE	[0/45/0/45/0/45/0/45]
J2	1	E-Glass	Derakane 470 HT-400 VE	[0/0/0/0]
CE1	1	Carbon/glass	Pro-set INF 114/211	[V(± 45)g/0c] _S
CE2	1	Carbon/glass	Pro-set INF 114/211	[V(± 45)g/0c] _S
CE3	1	Carbon/glass	Hexion RIMR 035c/RIMH 0366	[V(± 45)g/0c] _S
CE4	1	Carbon/glass	Hexion RIMR 035c/RIMH 0366	[V(± 45)g/0c] _S
CE5	1	Carbon/glass	Crestapol 1250PUL urethane Acrylate	Veil, E-BX 1700,[CLA 1812]2, E-BX 1700, Veil
CE6	1	E-Glass	AME 6001 VE	Veil, E-BX 1700,[CLA 1812]2, E-BX 1700, Veil
C32,C33	18	Carbon		0/90
C34, C35	18	Carbon		0/90
C36, C37	18	Carbon		0/90
C38, C39	18	Carbon		0/90

Biofouling & Environmental Exposure for MHK Coatings

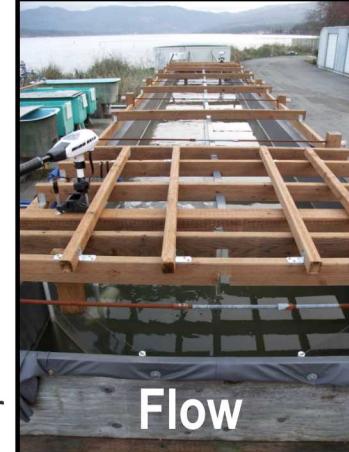


PNNL Marine Sciences Laboratory in Sequim, WA

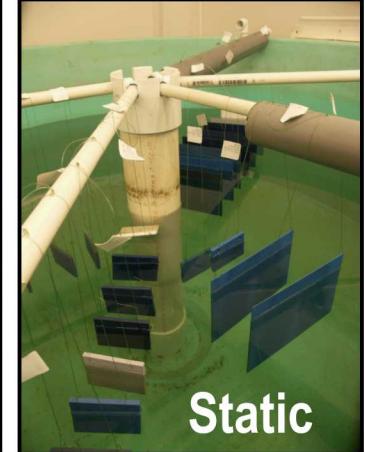
Determine Environmental Exposure Effects on Commercial & Sandia MHK Specific Coatings.

Evaluate under static & flow conditions with unfiltered natural seawater.

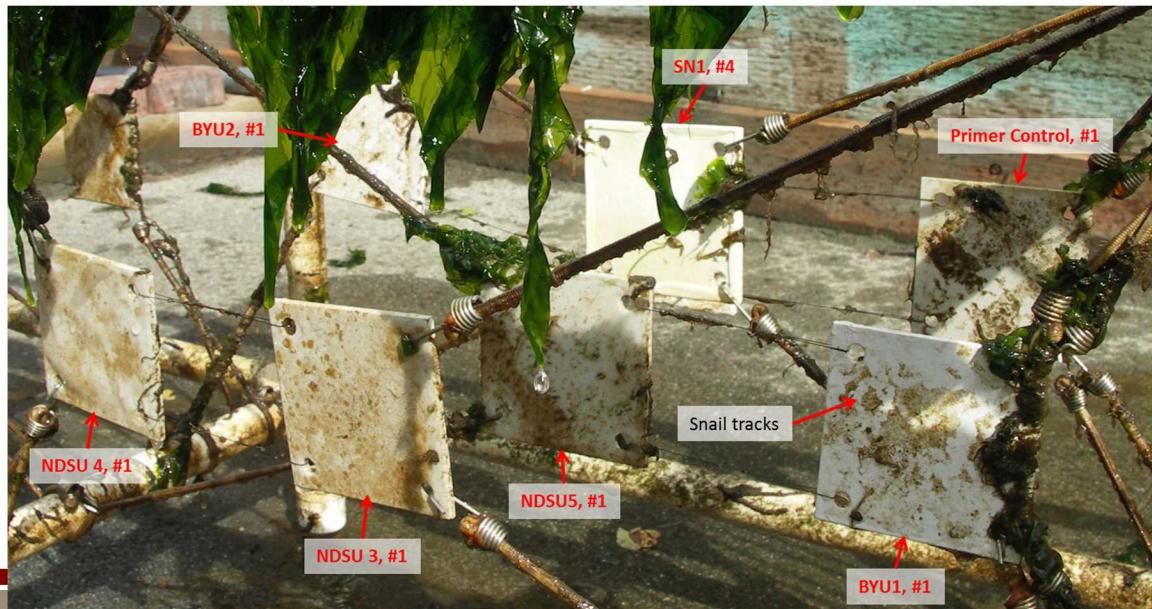
- MHK not operating under shipping conditions!



Flow



Static





- ▶ Glass fiber Reinforced Plastic (**GRP**)
- ▶ Polystyrene (**PS**)
- ▶ Polyethylene (**PE**)
- ▶ G10 Garolite Fiberglass (**G10, aka FR4**)
- ▶ Poly(phthalazinone ether amide) (**PPEA**)
- ▶ Poly(2,6-dimethyl-1,4-phenylene ether) (**PPE**)
- ▶ Nylon 11 (polyamide) (**PA11**)
- ▶ Polyamide 6 (**PA6**)
- ▶ Polyethylene Terephthalate (**PETG**)
- ▶ *Poly(ethylene terephthalate)* (**PET**)
- ▶ Carbon-carbon composite (**HDP**)
- ▶ **Aluminum**
- ▶ **Sanded Aluminum**
- ▶ **Stainless Steel**
- ▶ **Carbon Steel**

Fouling Tests



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- ▶ Commercial coatings and paints
 - Except when integrated with a company's composite material
- ▶ Commercially available and emerging composites materials
- ▶ Samples provided by composites manufacturers, MHK systems, coatings manufacturers (~500 individual coupons)
- ▶ Tests under MHK-relevant velocities (0.1 m/s and 2.6 m/s)
- ▶ Exposures from 6 months to 20 months
- ▶ Analyses: TOC/N, image analysis, wet/dry weight
- ▶ Results will be made public, but proprietary information about coatings and composites formulation and manufacture may not



► Coatings

- Priming and adhesion failing on some surfaces
 - Improper preparation? (e.g., sanding to roughen)
- Failures on tapered and narrow edges (cracking, delamination)
- Copper-based paints are incompatible with aluminum structures, even with primer coats
- Soft/flexible/elastic materials are very difficult to protect
 - Long term potential effects of sulfur redox and embrittlement are largely unknown

► Materials

- Water intrusion into some composites is a challenge (edges, holes, seams); may lead to weakening, swelling, deformation
 - Potential impact on modular designs

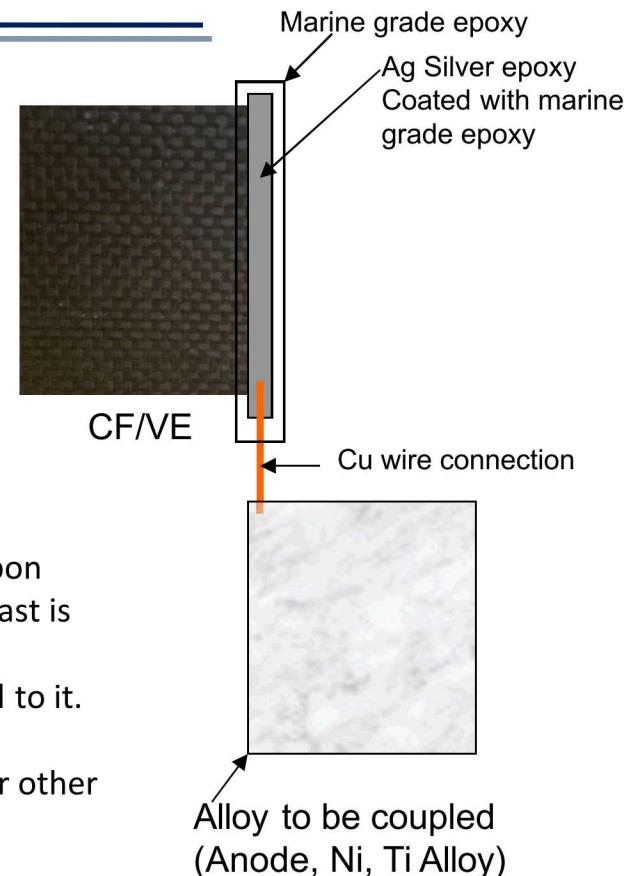
Material Design Tools for Marine and Hydrokinetic Composite Structures

Metal – Carbon Fiber Composite Interconnects in Seawater

Corrosion can occur on metals connected to carbon fiber composite materials (i.e., CF composite to metal interconnects). FAU is testing galvanic coupling of metal and CF composites.



A portion of a carbon fiber composite mast is shown, with metal couplings attached to it. Metal could be Aluminum, steel or other alloy.



Materials

FAU

FLORIDA ATLANTIC

UNIVERSITY

Fiber

- Carbon fiber:
-T700 (Toray)

-- Sizing

- FOE sizing

Matrix

- Vinylester:
 - Derakane 8084
 - Derakane 510A

Materials Systems

- CF/VE 8084
- CF/VE 510

Environmental conditions

- Sea Water /RT
- Sea Water 100°F

Alloys used for Composite Metal Interconnect

- Connected to Anode (Al or Zn)
- Connected to Ti alloy mesh
- Coupled to Ni foil

Panels were prepared in 2009 and were RT cured (i.e., no elevated temperature post-cure).
10 cm x 10 cm were cut from a larger panel during Summer 2017.

Laminates were manufactured by vacuum assisted resin transfer molding (VARTM). (Unidirectional longitudinal direction)

F – Designed for vinyl ester, compatible with epoxy. O indicates with sizing and E indicates amount (0.7%)

Industry Assessment

- Questionnaire for industry input
- Phone interviews
- Identify:
 - What materials are being used
 - Gaps in existing data
 - Design and manufacturing challenges
 - Components where composites may be used
- Results inform the development of subcomponent types

Material Design Tools for MHK Composites Structures

Industry Assessment

Thank you for participation. The purpose of this assessment is to help DOE identify what the MHK industrial needs are for materials and sub-components. Your answers will help pinpoint where materials and sub-components are limiting or hindering your technology.

Technology Name

Technology Resource

Technology Readiness Level

What types of composite materials are currently being used in structural components? (Check all that apply)

Reinforcement:

<input type="checkbox"/> glass	<input type="checkbox"/> carbon	<input type="checkbox"/> aramid	<input type="checkbox"/> other
<input type="checkbox"/> short fiber	<input type="checkbox"/> random fiber	<input type="checkbox"/> woven fiber	<input type="checkbox"/> other

If other, please describe

Matrix:

<input type="checkbox"/> vinyl ester	<input type="checkbox"/> epoxy	<input type="checkbox"/> other
--------------------------------------	--------------------------------	--------------------------------

If other, please describe

Are there existing metal structures or components that have been considered for replacement with composite material, but not implemented due to data gaps?

If Yes, what specific data gaps that have prevented the use of composites? (check all that apply)

<input type="checkbox"/> strength	<input type="checkbox"/> environmental effects	<input type="checkbox"/> fatigue	<input type="checkbox"/> other
-----------------------------------	--	----------------------------------	--------------------------------

If other, please describe

What types of joints are used or of interest for your applications? (check all that apply)

<input type="checkbox"/> composite-to-composite	<input type="checkbox"/> metal-to-composite
<input type="checkbox"/> bolted	<input type="checkbox"/> adhesively bonded
	<input type="checkbox"/> other

Would you be willing to supply detailed description of currently used small sub-components (e.g. composite joints) most susceptible to marine environmental effects?

Would you be willing to work with the DOE to develop and produce samples for testing small sub-components?

Are there any additional concerns related to composites reliability or design issues?

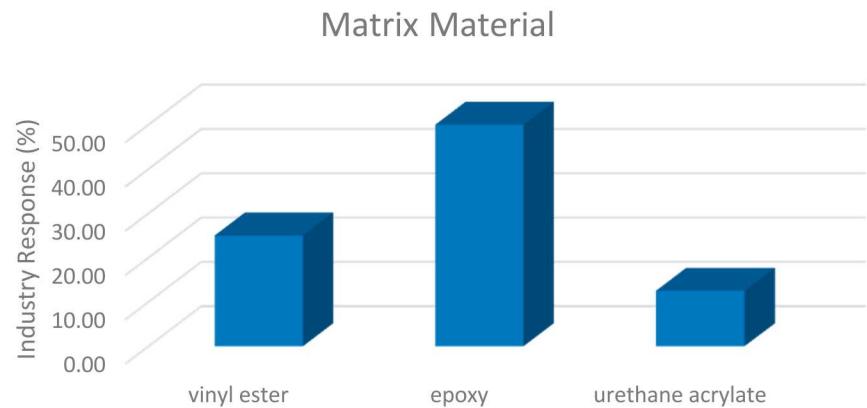
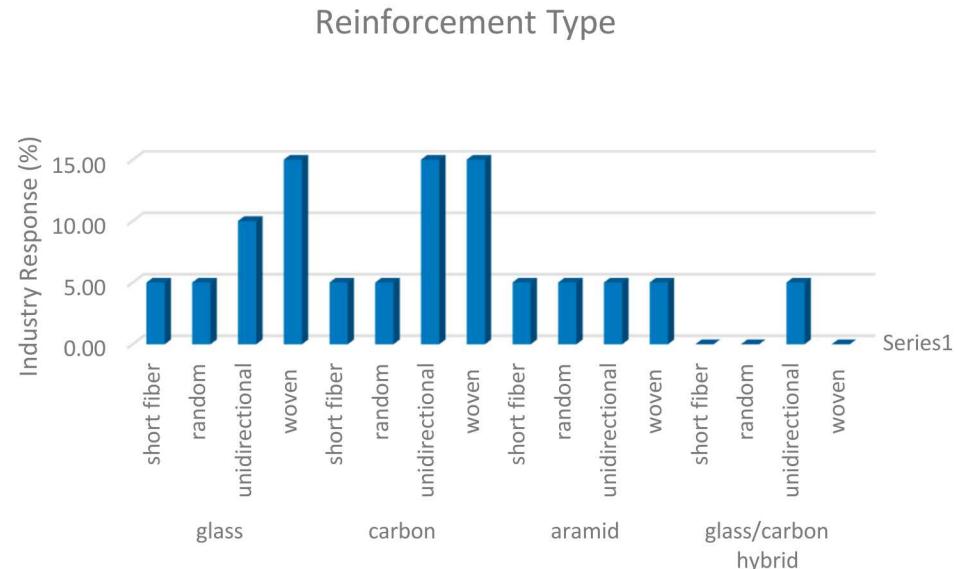
No

No

No

Industry Assessment - Composites in use

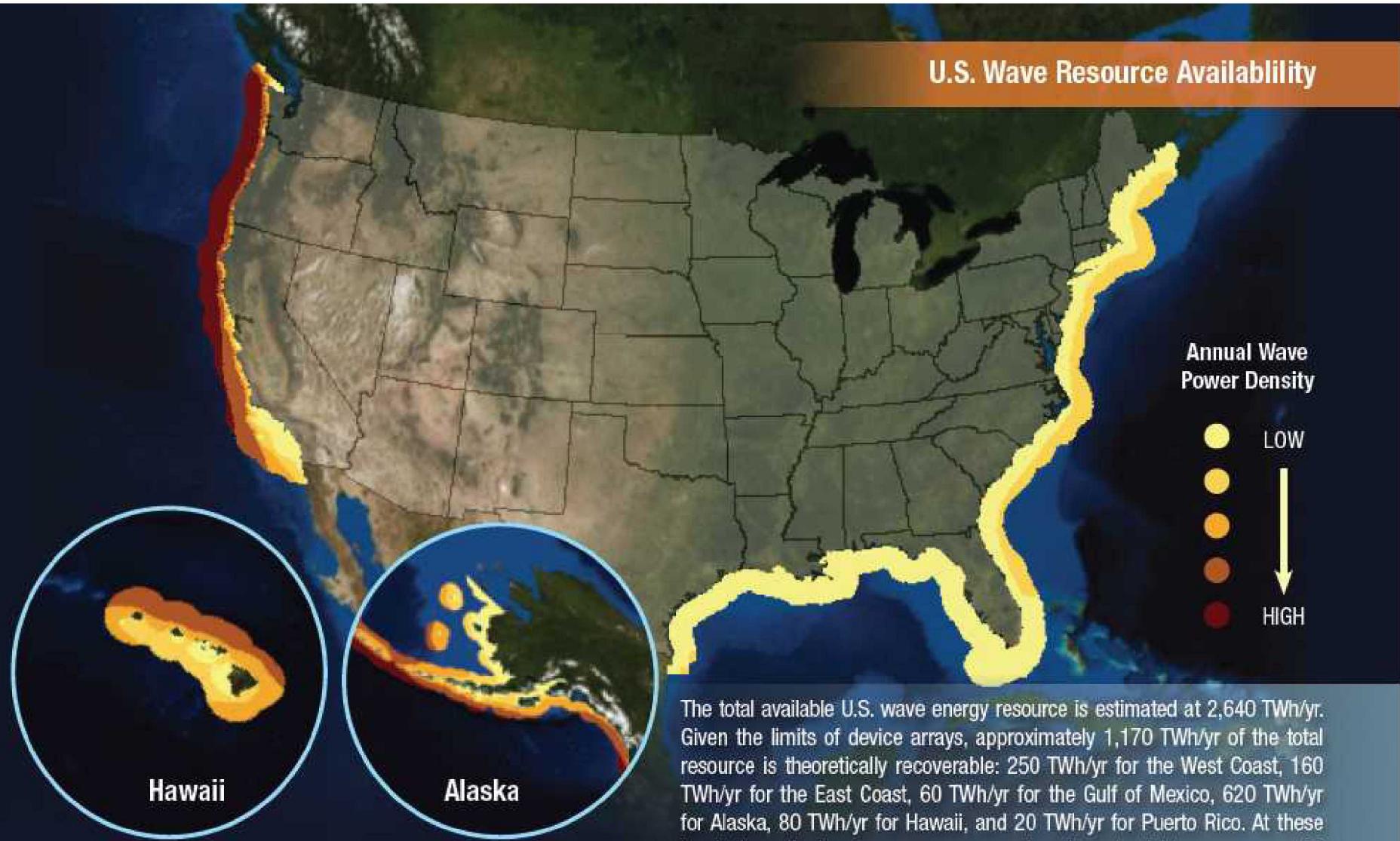
- Variety of structural laminates currently used
- Fiber reinforcements
 - Fiberglass
 - Carbon
 - Limited use of Aramid
- Matrix materials
 - Vinyl Ester and Epoxy most common



What we have learned.

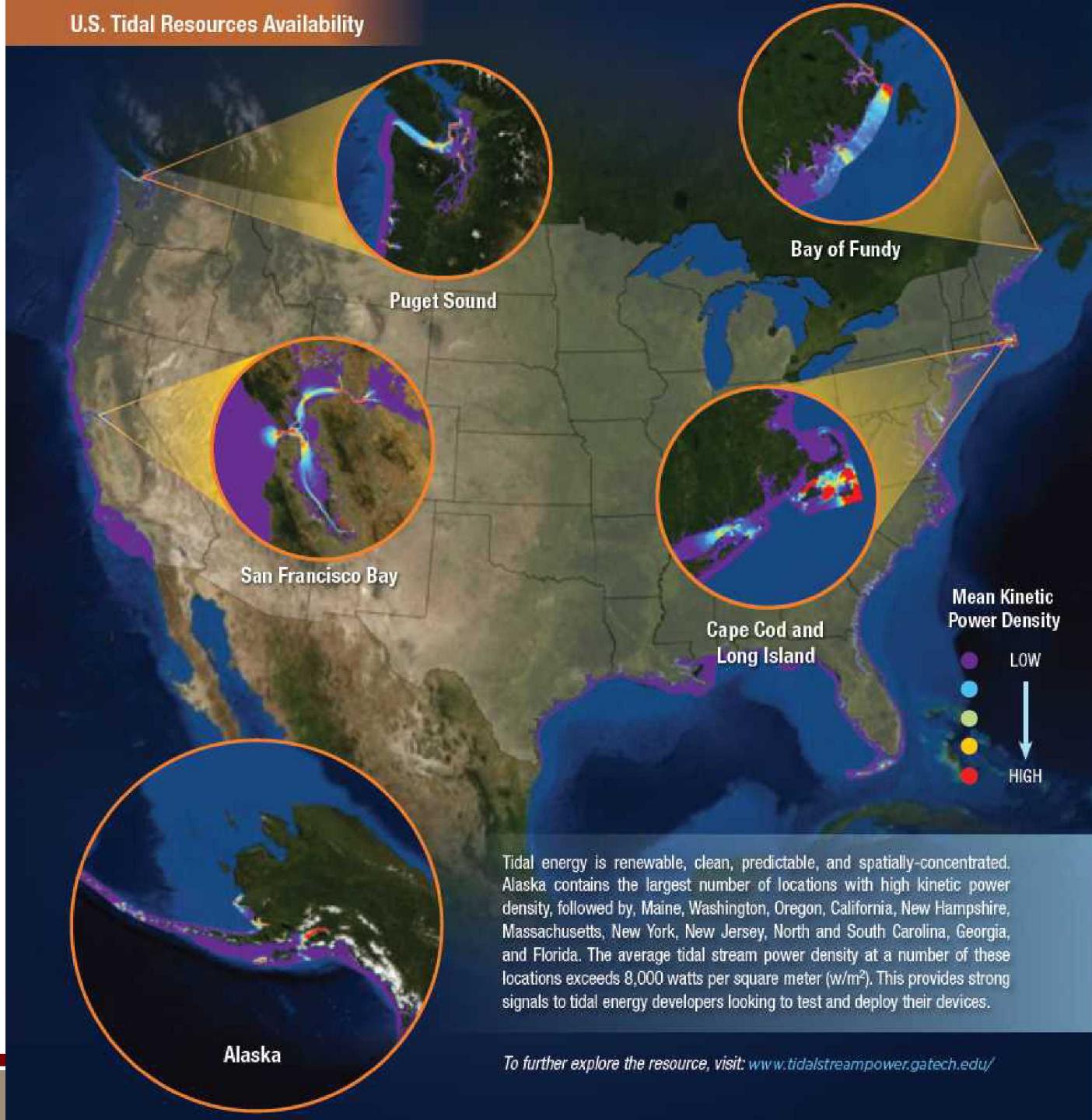
- Water absorption into composites impacts materials properties (composite performance, accelerated corrosion- carbon based)
- Not all antifouling coatings are created equal. MHK has its own conditions.
- What does the MHK industry needs for subcomponent testing?
- Corrosion: anode samples are corroding and calcareous deposits have formed on the interconnected composites.
- Results on samples from industry have been explored and will be downloaded to our database.
 - This public information is garnered to support design decisions.

U.S. Wave Resource Available Along our Coasts total ~2,640 TWh/yr.



To further explore the resource, visit: maps.nrel.gov/mhk_atlas

SAND2017-9281 C



Tidal energy is renewable, clean, predictable, and spatially-concentrated. Alaska contains the largest number of locations with high kinetic power density, followed by, Maine, Washington, Oregon, California, New Hampshire, Massachusetts, New York, New Jersey, North and South Carolina, Georgia, and Florida. The average tidal stream power density at a number of these locations exceeds 8,000 watts per square meter (w/m^2). This provides strong signals to tidal energy developers looking to test and deploy their devices.

To further explore the resource, visit: www.tidalstreampower.gatech.edu/