Advances in Large Scale Additive Manufacturing Using Bio-Based Materials

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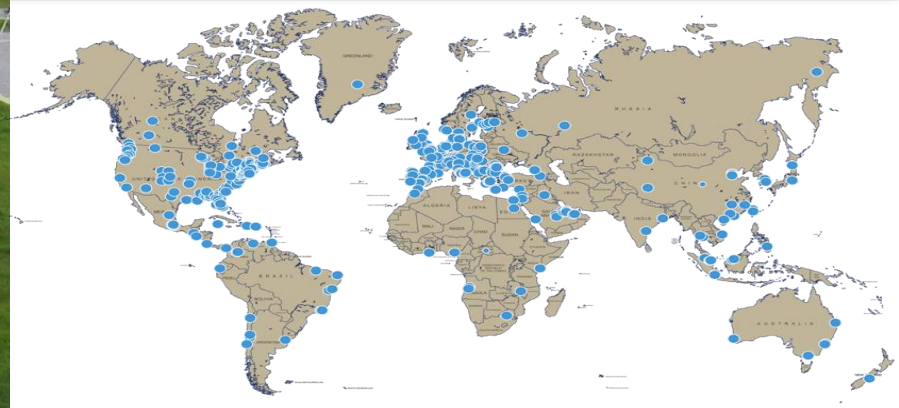
Keynote
Composites Industrial Revolution Conference
May 6, 2021

ORNL is managed by UT-Battelle, LLC for the US Department of Energy



- **Largest university-based Research Center in Maine**
- **Founded through the NSF in 1996**
- **260 personnel**
- **100,000 ft² facility**
- **2,600+ students from 35+ majors**
- **>10 spinoff companies**
- **>1,000 publications**
- **>80 patents issued**
- **> 30,000 visitors**
- **> 1,600 media stories**

Outline

- Hub and Spoke
- Cellulose AM feedstock
- Tech roadmap
- Funding for industry collaborations
- Applications: Boatbuilding, Offshore wind, formwork, bridges, culverts

ORNL Research Team


Soydan Ozcan, Project Lead

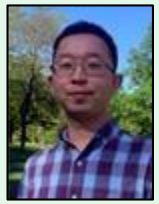

Craig Blue, Adv. Mfg. Program Manager


Bill Peter, MDF Director


Halil Tekinalp, Composite processing


Vlastimil Kunc, Large area composite AM


Brian Post, AM systems design


Kai Li, Polymer chemistry


Meghan Lamm, Polymer chemistry


Andy Zhao, Composite processing


Greg Larsen, Composite processing


Pum Kim, AM modeling


Katie Copenhaver, Composite processing


Loukas Petridis, High performance computing


Kristina Armstrong, Energy analysis


Uday Vaidya, Composite processing

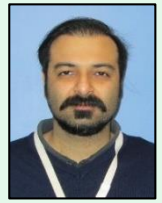

Ahmed Hassen, Composite processing


Art Ragauskas, Materials chemistry


Kris Villez, AM modeling


Chris Hershey, Composite processing


Vidya Kishore, Composite processing


Sam Bhagia, Materials chemistry


Jesse Heineman, AM systems design


Matt Korey, Composite recycling


Alex Roschli, AM systems design


Phillip Chesser, AM systems design


Vincent Paquit, AM modeling

UMaine Research Team


Habib Dagher, ASCC Director


Doug Gardner, Project technical lead


James Anderson, AM technical lead


Susan MacKay, Program manager

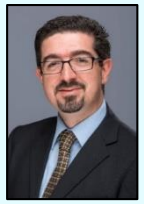

Hemant Pendse, FBRI Director


Colleen Walker, PDC director


Carl Tripp, Materials chemistry


Will Gramlich, Polymer chemistry


Dave Neivandt, Materials engineering


Mehdi Tajvidi, Forest products processing


Lu Wang, Composite processing


Yousoo Han, Forest products processing


Donna Johnson, Nanocellulose processing


Amy Luce, Forest products processing

Jason Stevens, Forest products processing

Andrew Foster Materials charact.

Madeline Wehrle, Composite engineering

Scott Tomlinson, Large area composite AM

Joe Kerr, AM modeling

Rich Fredericks, Large area composite AM

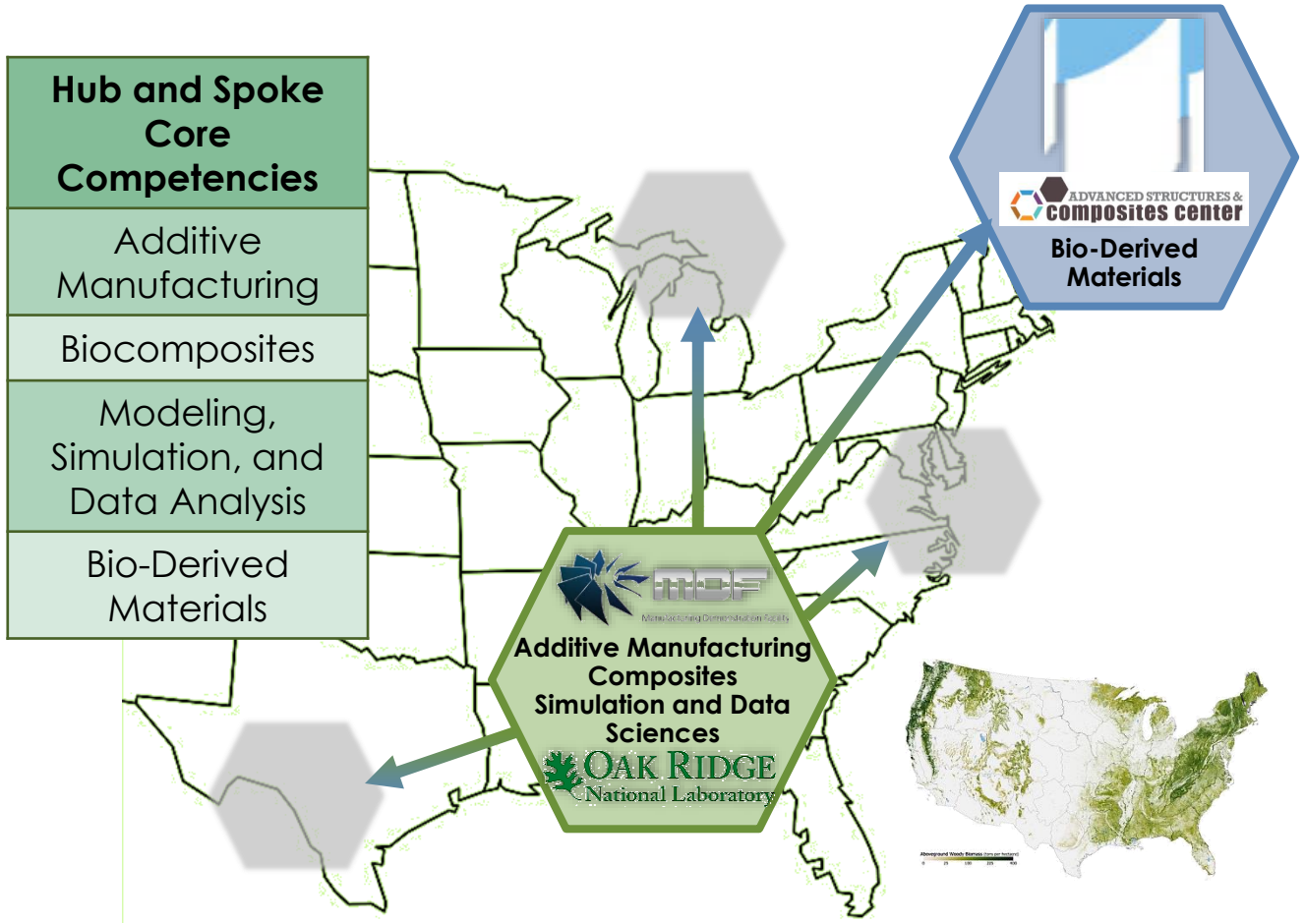
Wes Bisson, Large area composite AM

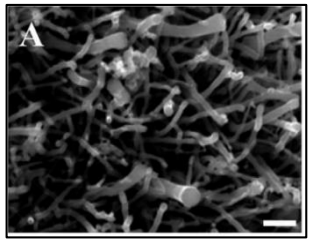
Mike McCarty, Large area composite AM

ORNL & U-Maine Hub & Spoke Program

Sustainable Forest Products for Advanced Manufacturing

- **Connects a $2 Billion national laboratory to local ecosystems.**
- **Maine lost 5 of its paper mills**
- **ASCC is the largest univ.-based research Center in Maine, 260 personnel**
- **Combines MDF-ORNL expertise in advanced manufacturing with UMaine innovation in forest derived biocomposites**
- **Facilitates access to ORNL and UMaine assets and expertise to bring new, sustainable, and functional materials and processes to the market**





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THE UNIVERSITY OF MAINE | ADVANCED STRUCTURES & composites center

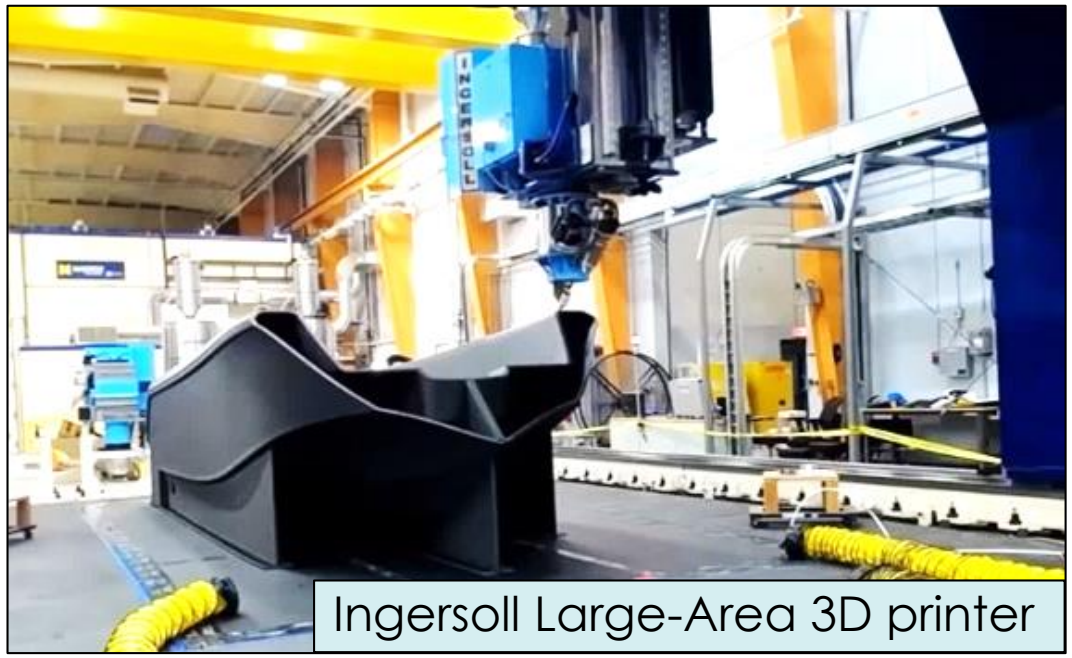
Hub & Spoke Timeline

2016 | 2017 | 2018 | Launch 2019 | 2020 | 2021 . . . | 2025 . . .

- ORNL visits UMaine as part of EDAT
- ORNL and Ingersoll co-develop the world's largest 3D printer
- MOU—Initial agreement between UMaine and ORNL
- ORNL funds first pilot project with UMaine

- **DOE initiates $20M partnership for Phase I**
- Ribbon cutting for 3D printer at UMaine, set Guinness record for world's largest printer and printed object
- Two technical workshops
- **Start of Phase II**
- Industry roadmapping workshop

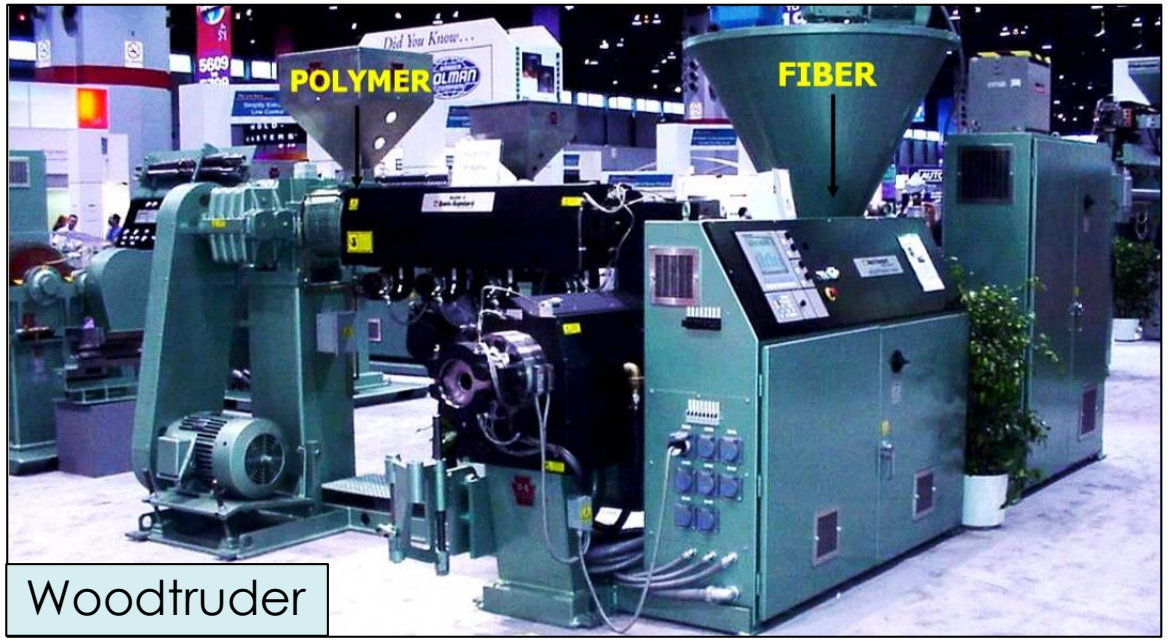
Resources at the University of Maine



Ingersoll Large-Area 3D printer

- Cellulose supermass colloider
- Industrial pulping, bleaching, and refining lines
- Industrial spray dryer
- "Nano" ultrasonic spray dryer
- Injection molding equipment
- Melt compounding equipment
- Twin screw extruder
- Polymer and composite characterization suite (molecular, bulk, thermal, and mechanical characterization)
- Shredding, grinding, granulating, and pelletizing equipment


Process Development Center (CNF production)



Woodtruder

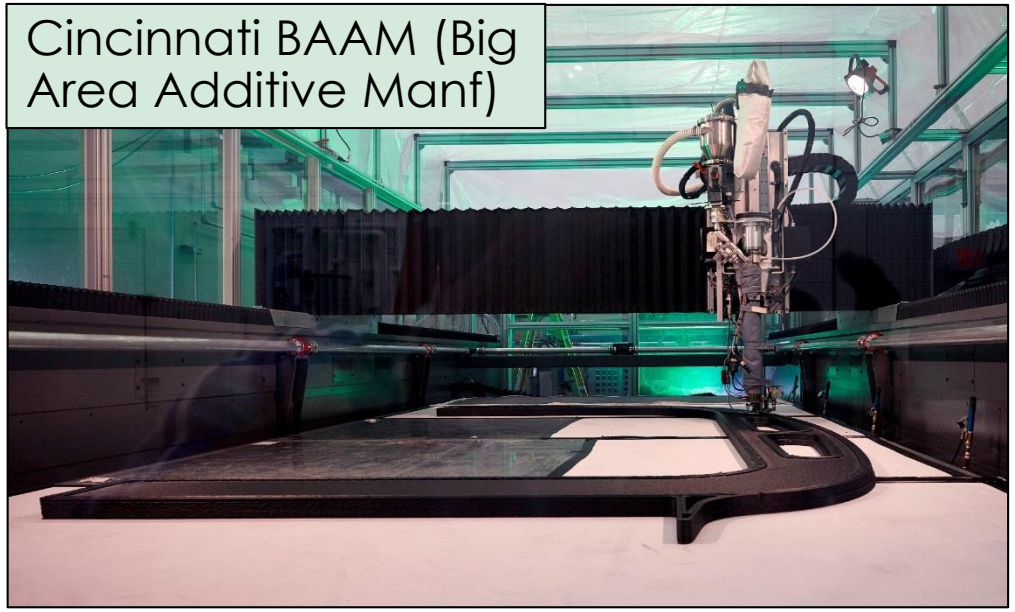
Resources at MDF and ORNL

Summit supercomputer

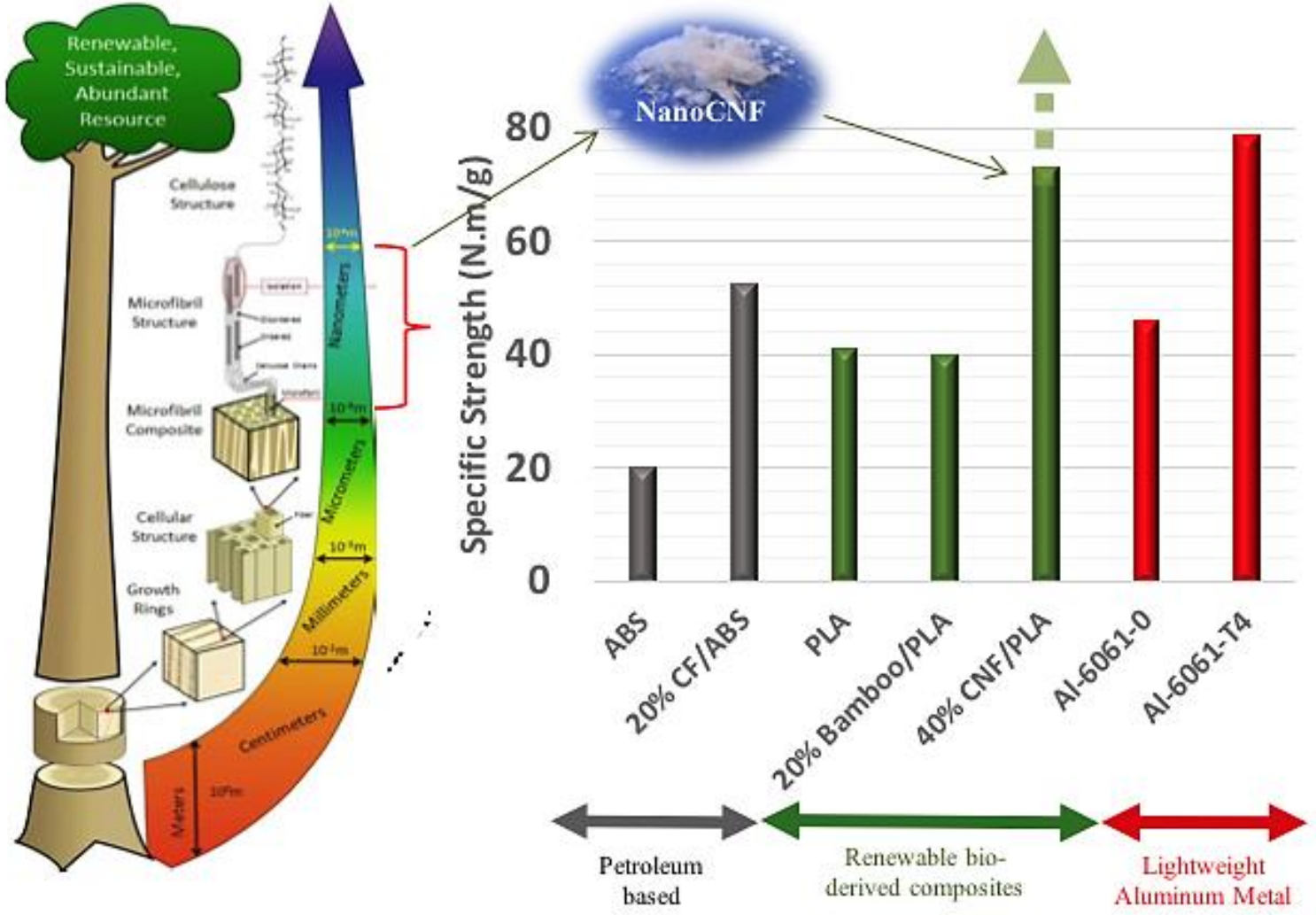
State-of-art characterization and manufacturing eqpt.

- Injection and compression molding equipment
- Melt compounding equipment
- Multi-material and reactive additive manufacturing equipment
- Polymer and composite characterization suite (molecular, bulk, thermal, and mechanical characterization)
- Large-area thermoset printer
- Spallation neutron source and high-flux isotope reactor for advanced materials characterization

Cincinnati BAAM (Big Area Additive Manf)



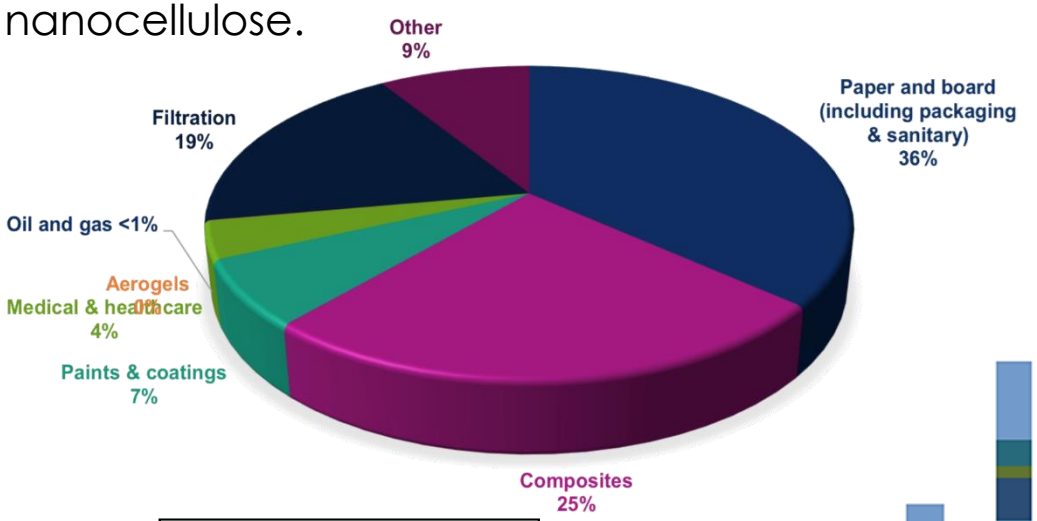
Cellulose as a bio-alternative to fossil-derived materials



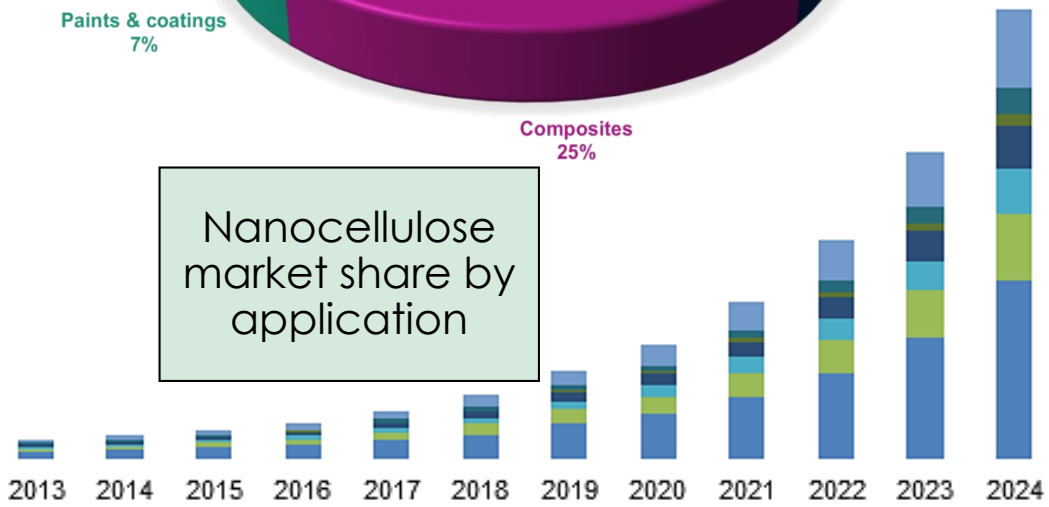
	Carbon Fiber (CF)	Cellulose nanocrystal (CNC)
Density (g/cm^3)	1.8 - 2.2	1.5
Tensile Strength (MPa)	4000	10,000
Modulus of Elasticity (GPa)	235	150
Cost ($/lb)	>10	<2-5
Sustainable	NO	**YES**

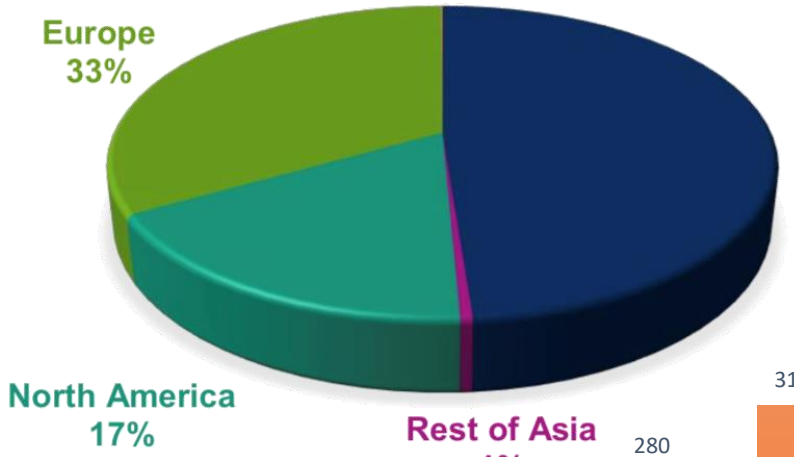
Nanocellulose Competitive Landscape

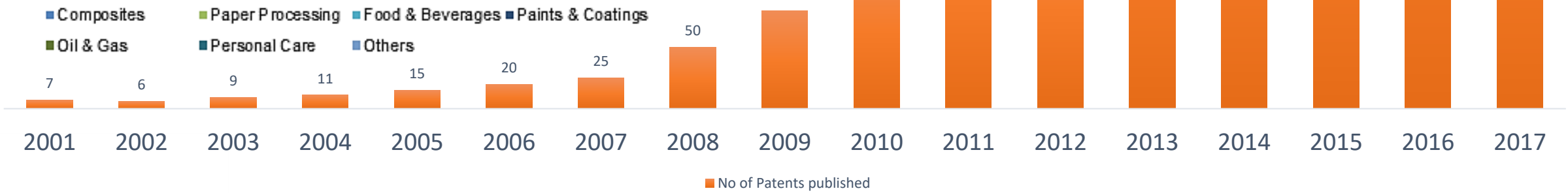
Global government spending on CNF R&D is over $1B to date. Israel, Germany, France, Sweden, Finland, Switzerland, Norway, and Japan have all built dedicated pilot or demonstration plants of different capacities for nanocellulose.



Nanocellulose market share by application







Hub & Spoke enables development of world's largest 3D printer, setting 3 Guinness records

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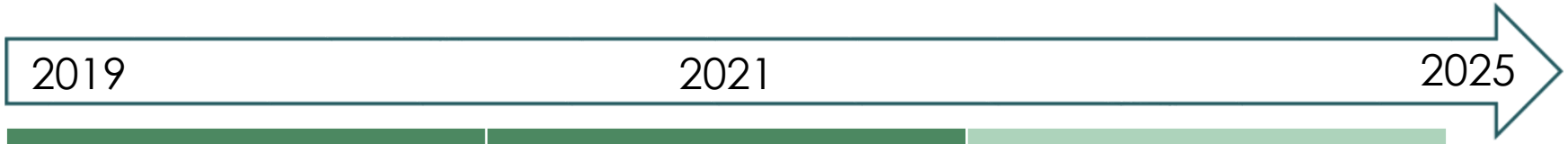
Hub & Spoke
Technology Roadmap



	Phase I	Phase II	Phase III
Materials Formulation	**Forest-based** wet fiber production, drying and surface modification	**Low/no water Cellulose Fiber production technology**	**Scale-up**, and **HPC simulations and modeling** applied to new bio-materials creation
3D Printing Process	optimization of **printing parameters**	Cost reduction through **lower cost** and **higher throughput** bio-based materials	**AI and Hybrid AM Systems**, machine learning.
AM Applications	Indirect and direct **tooling** applications	**Medium-scale**, medium throughput	**Large-scale, high throughput AM**

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Industry Technology Collaborations

Explore

- Opportunity for industry to discover and apply new manufacturing technologies

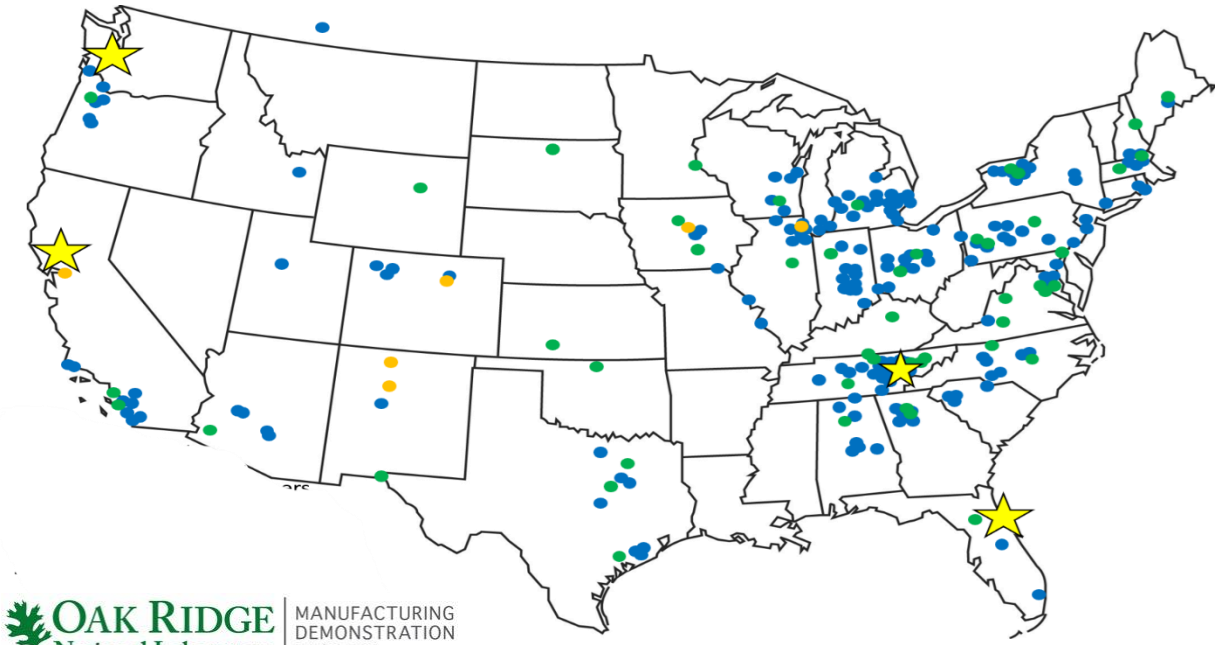
Engage

- Work with manufacturing staff to develop scope of work

Execute

- Phase 1 $40K
  Phase 2 $200K
- 1:1 Cost Match

Initiate 20 new projects annually to help commercialize new technologies



Domtar
NatureWorks
WBRC ARCHITECTS ENGINEERS
TECHMER PM POLYMER MODIFIERS
MITSUBISHI MATERIALS
atlantic SEA FARMS
Arcadia ALLIANCE
THE HINCKLEY COMPANY Since 1928
HODGDON VESSELS SINCE 1816
tpi COMPOSITES
INGERSOLL Machine Tools
CORESLAB STRUCTURES
Muddy River Aquaponics
shop
CINCINNATI CINCINNATI INCORPORATED
Valmet
sappi

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Hub and Spoke 2020 Highlights

16 tech collaborations in development

20+ published articles
3 cover articles

20+ graduate and undergraduate students

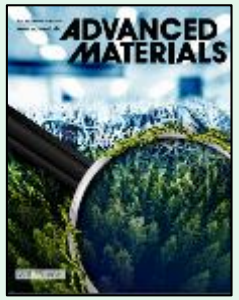
R&D100 2020 Award:
"Biomacromolecule Engineering by Soft Chain Coupling Technology"

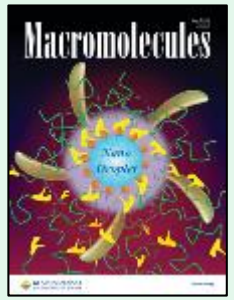
6 Conference presentations

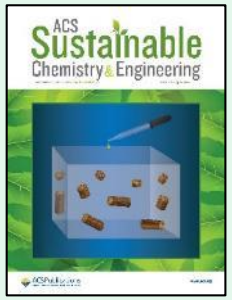
48 researchers

4 planned moonshot prints
- "tiny" house
- Wind blade root mold
- Indoor/outdoor office pod
- Oyster tanks

Business-sensitive: do not distribute







R&D 100 AWARDS

ITHEC 2020
5th International Conference & Exhibition on Thermoplastic Composites

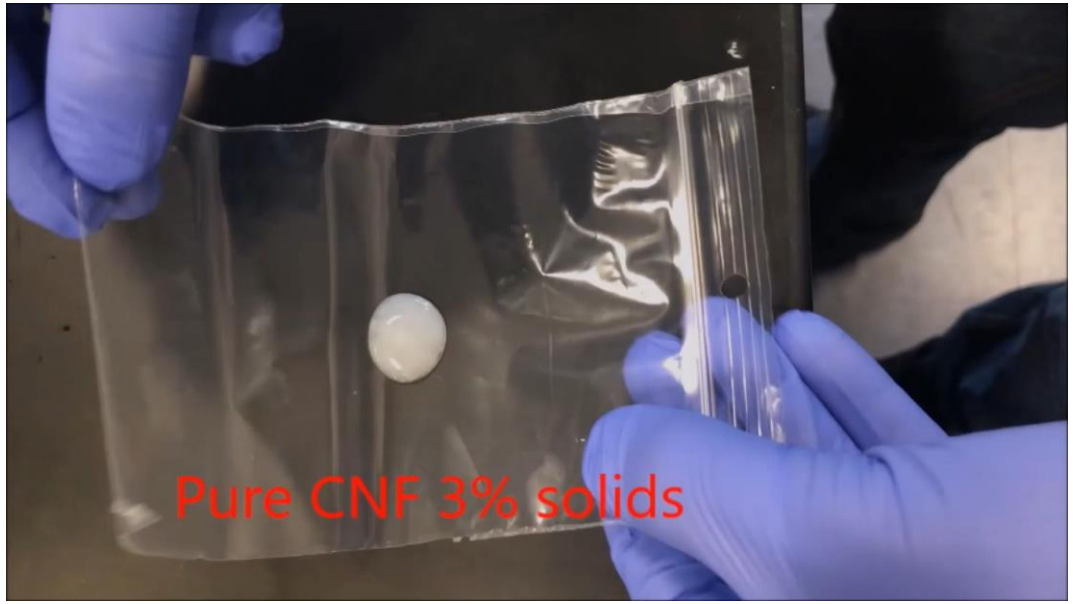
ACS Chemistry for Life®

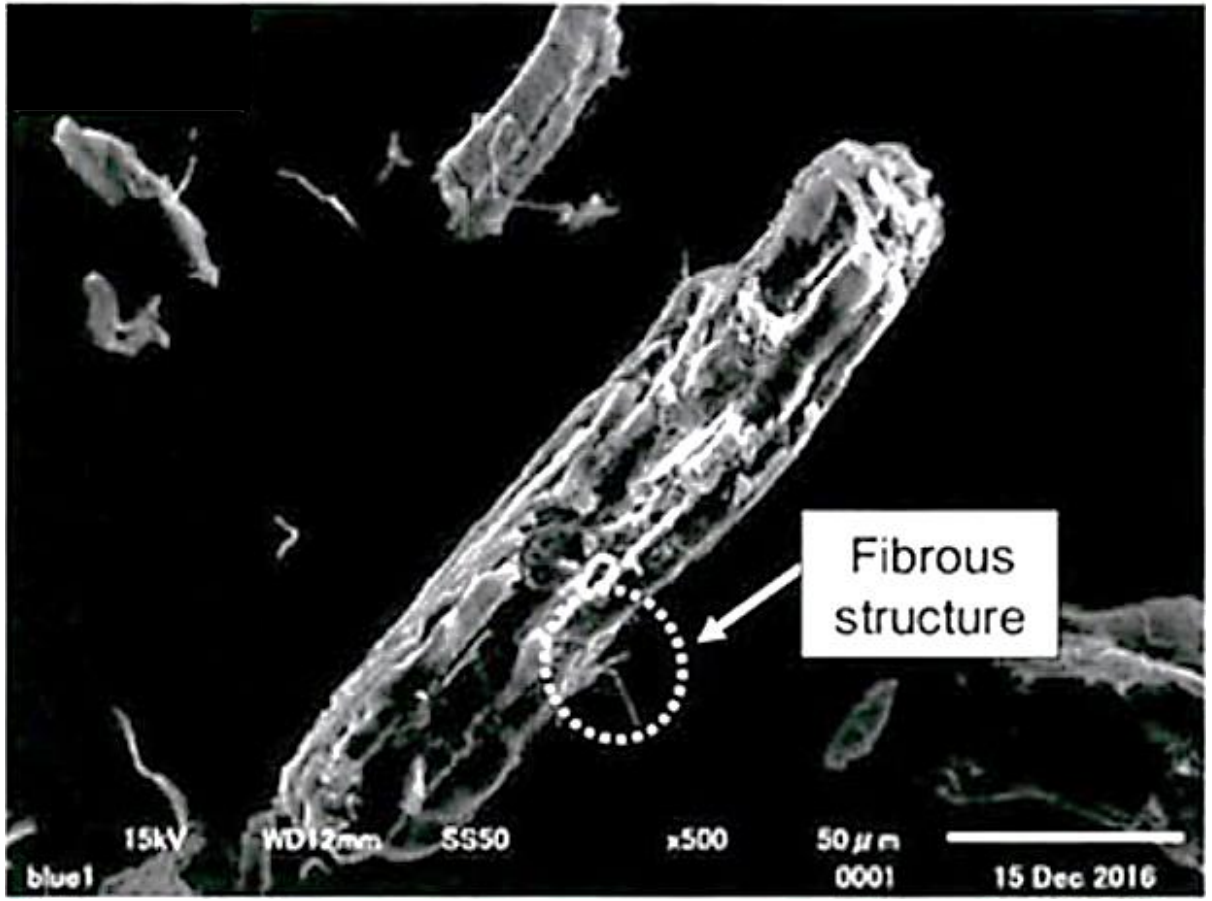
CAMX
THE COMPOSITES AND ADVANCED MATERIALS EXPO

Society of Wood Science and Technology - SWST - International

Novel CNF Drying
Contact Dewatering

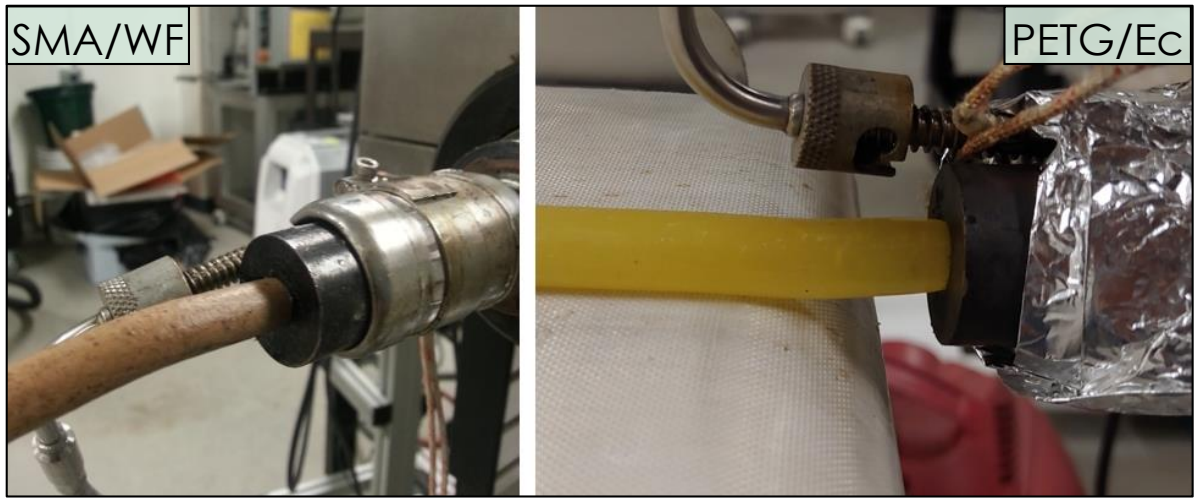
- CNF suspensions mixed with wood flour are pressed to convert bound water on CNF to free water and remove.
- Remaining water can be removed easily via air, oven, vacuum, or microwave drying.



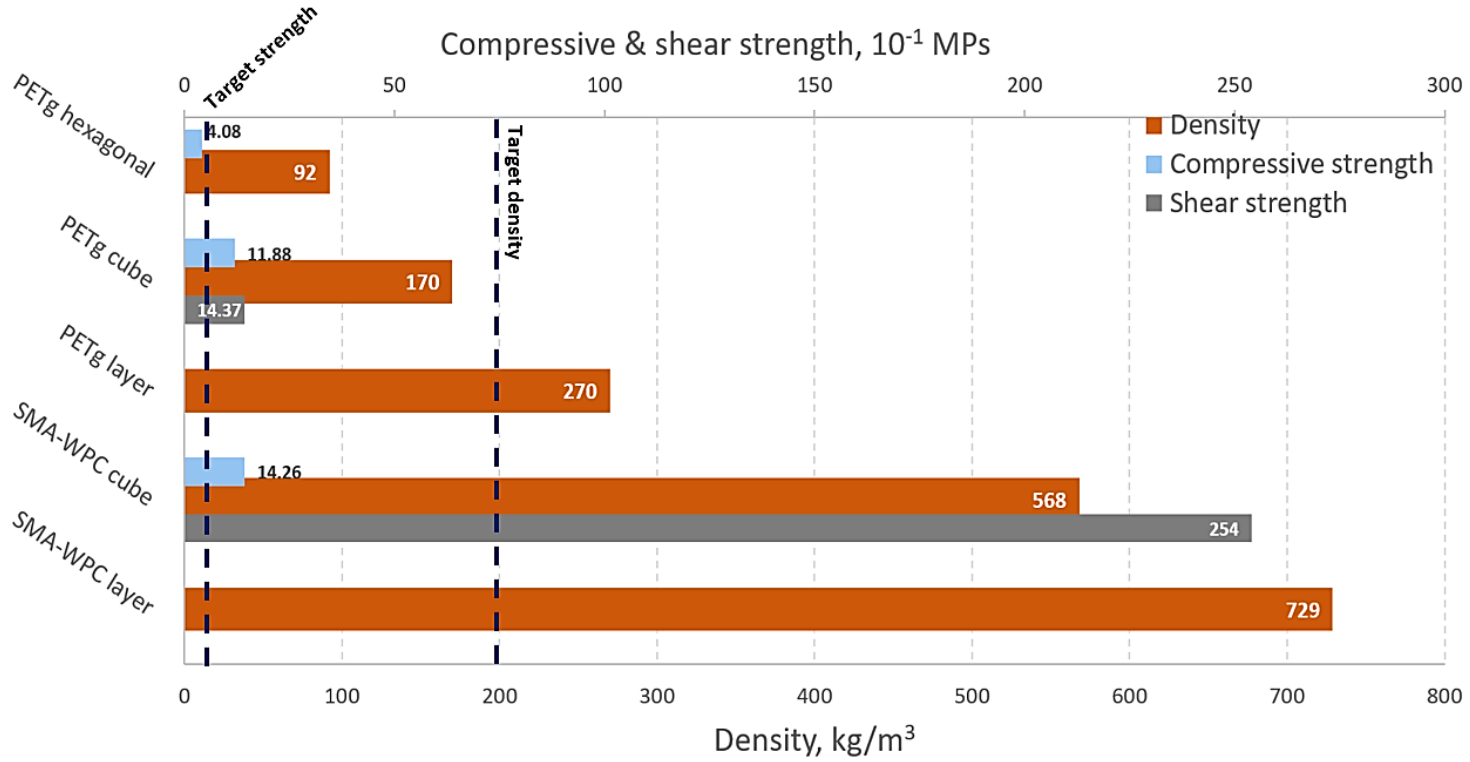


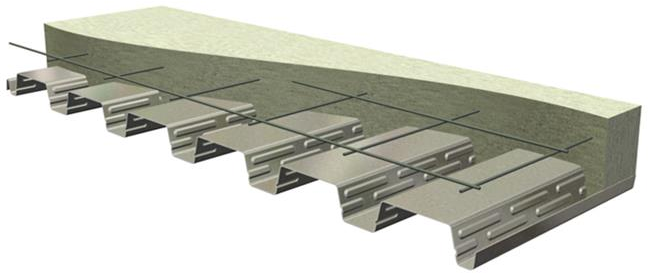
Formulation	Total Dry Mass (g)	Mass Pre-Dewatering (g)	Mass Post-Dewatering (g)	% Water loss (est.)
20% CNF	150	1501.5	388.4	**74.1**
10% CNF	150	1501.5	427.0	**71.6**

Foam printing



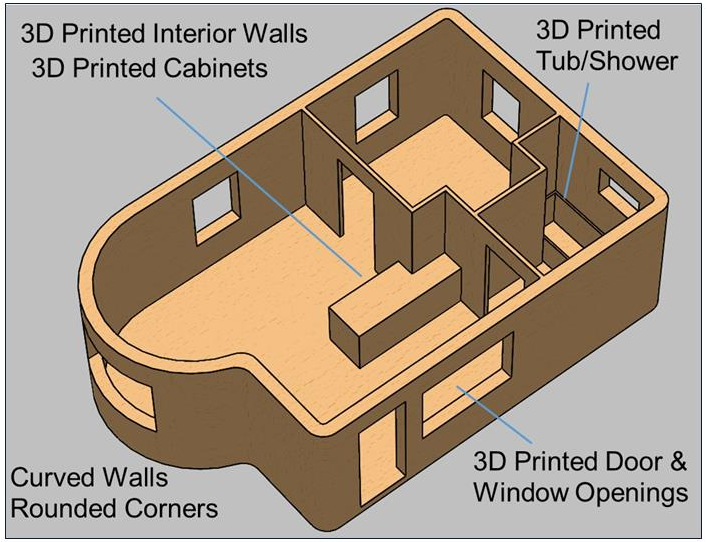
SMA/WF foams showed over **50% weight reduction**, and **PETG/Ec** showed an **86% weight reduction**.
Density of SMA: 1080 kg/m^3
Density of PETG: 1260 kg/m^3

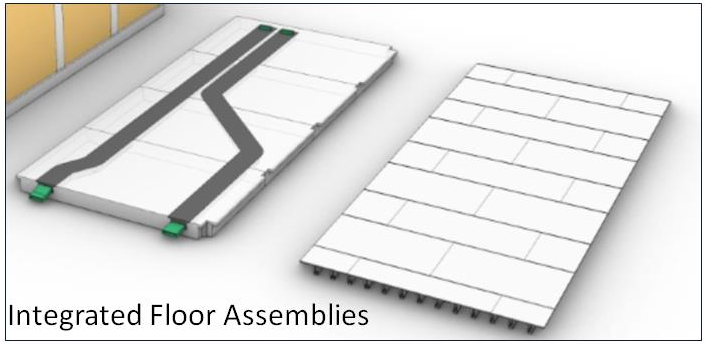




Formwork for Bridges

Roof Mold



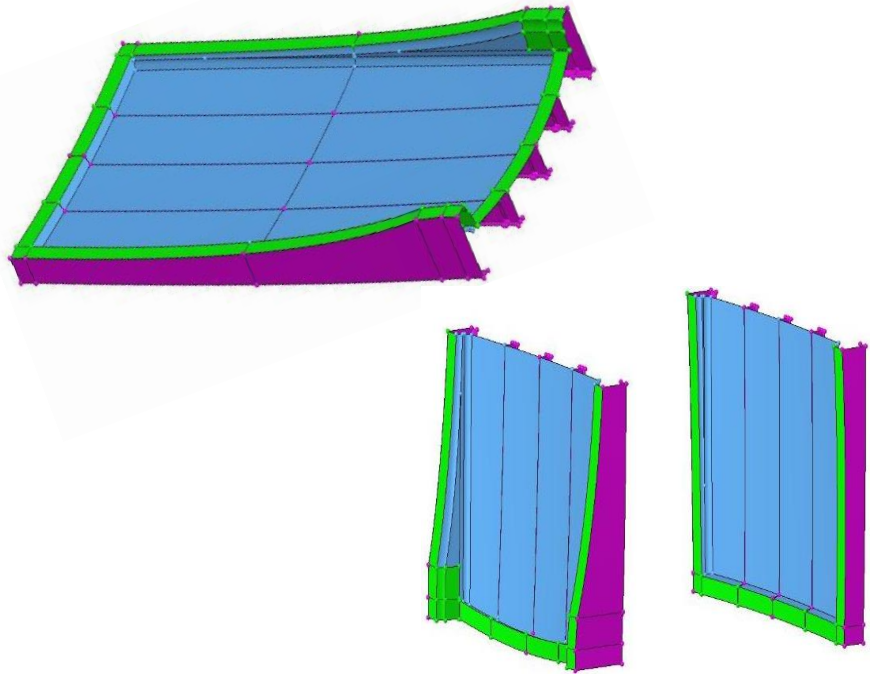


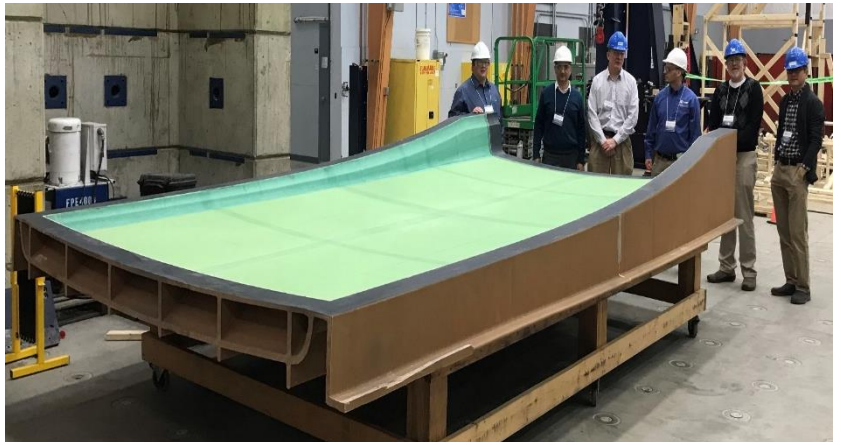
Transportation

Marine & Energy

Building Technology

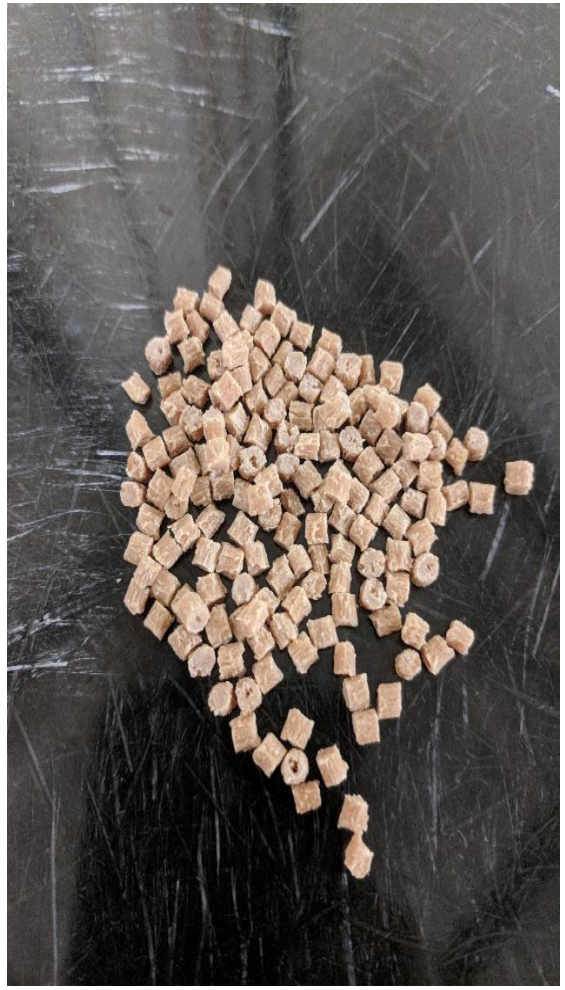
Hodgdon Yachts
10.5m Limo Roof Mold



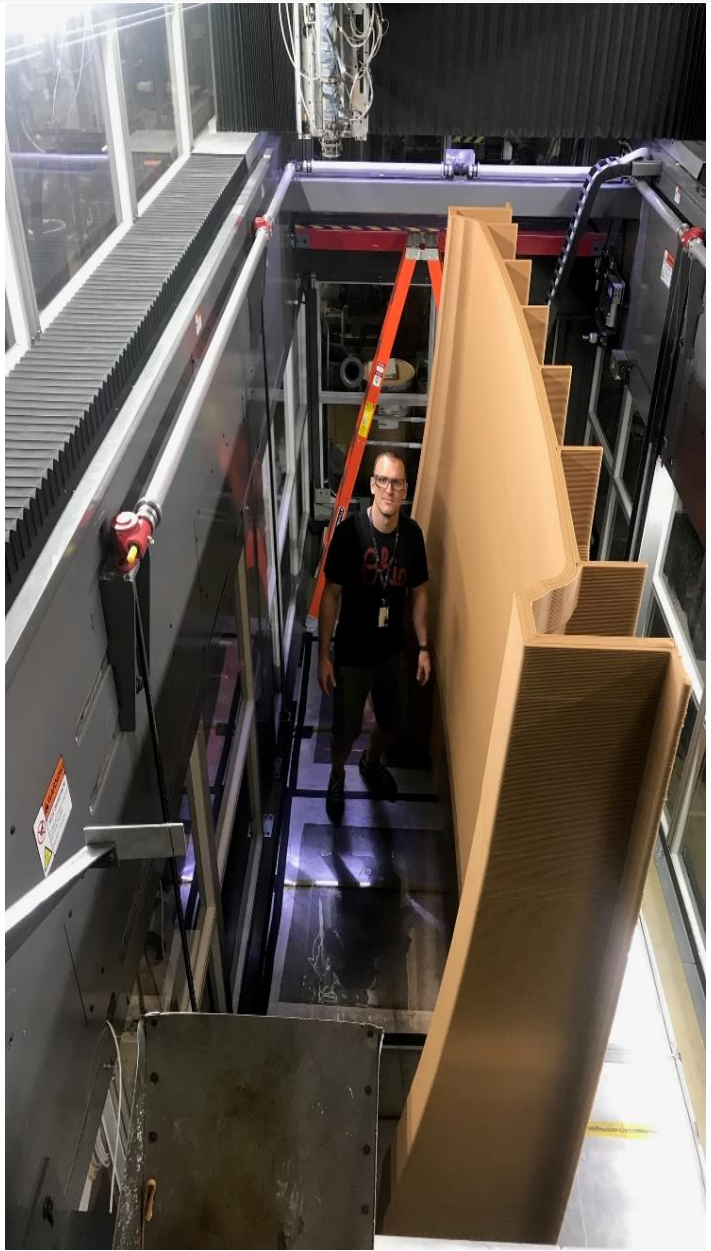


16’ x 8’, approx. 1,200lbs material

Printing Roof Tool-ORNL



PLA 20% Wood Flour + 1% CNF



UMaine and ORNL

Culvert Rehabilitation

Large scale 3D printing technology enables rapid manufacturing of complex shaped culvert diffusers at half the cost.

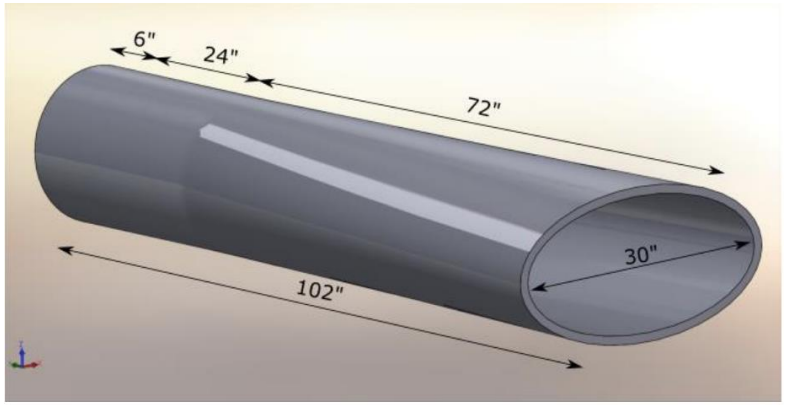
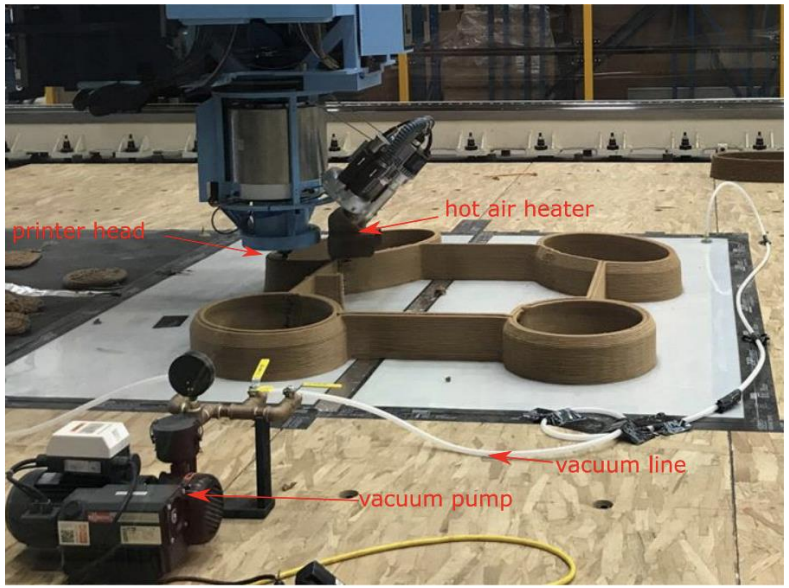
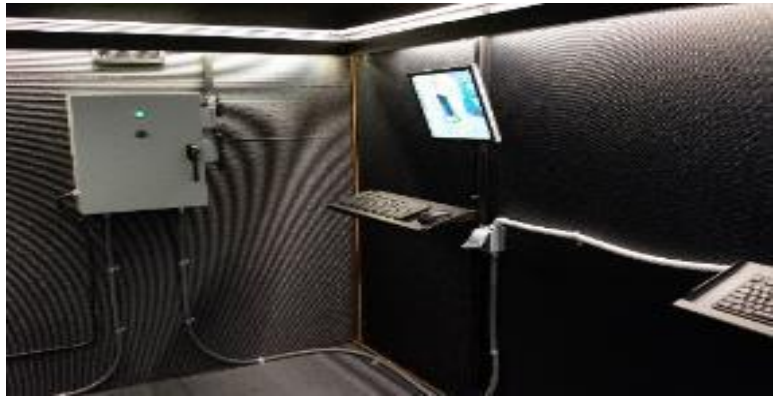


Figure 2: 3D model of the culvert diffuser prototype.

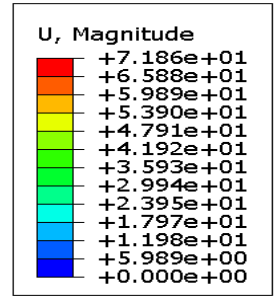


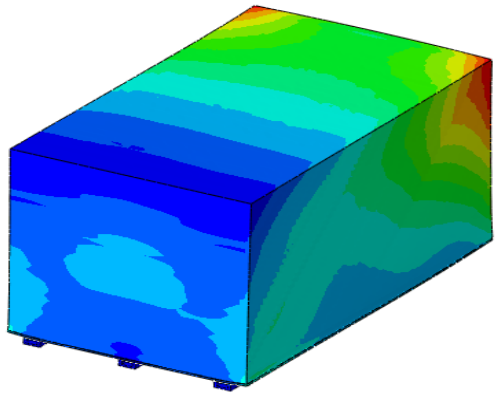
Future Applications – Energy Efficient Housing

Exposure: 8 Months Outdoors

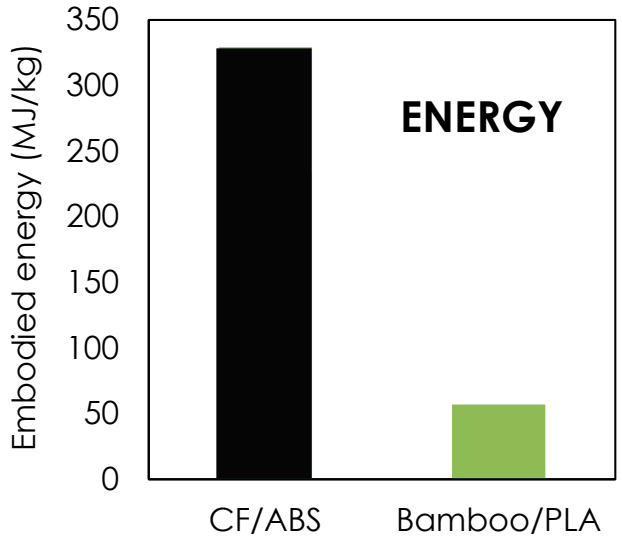


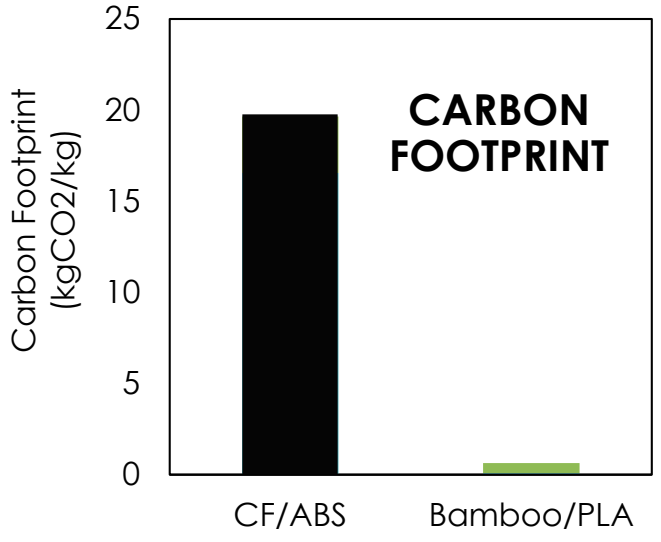
Thermal FEA Analysis

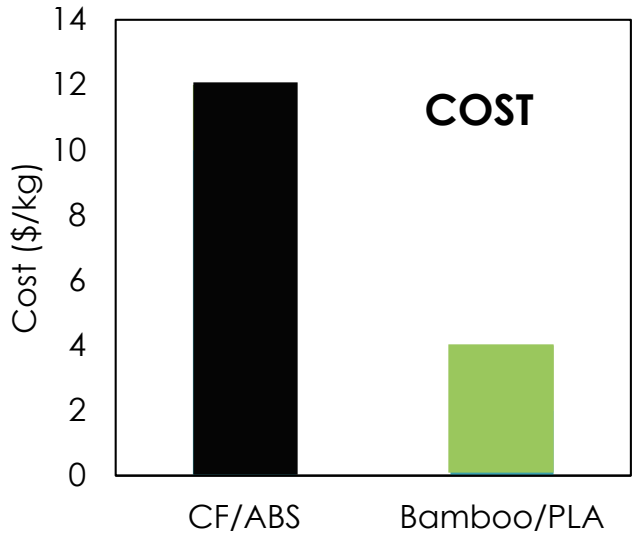


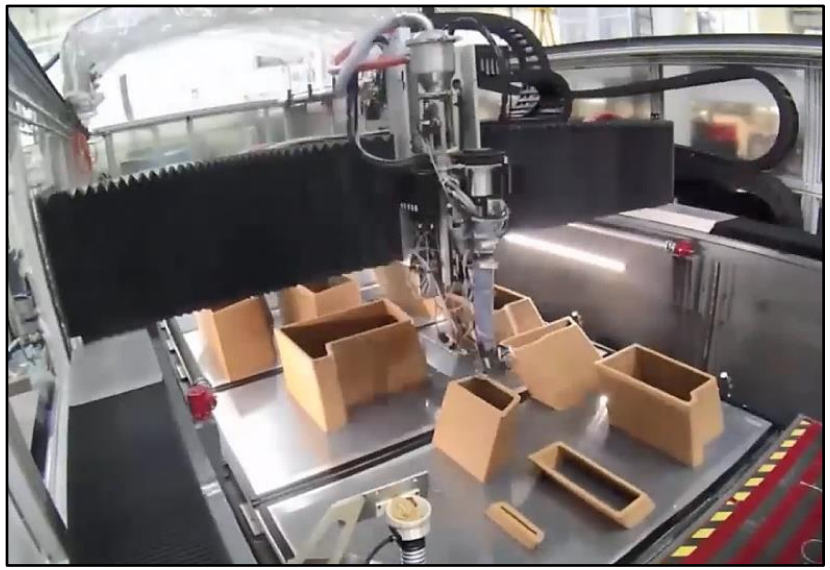


3D Printing Sustainable Structures









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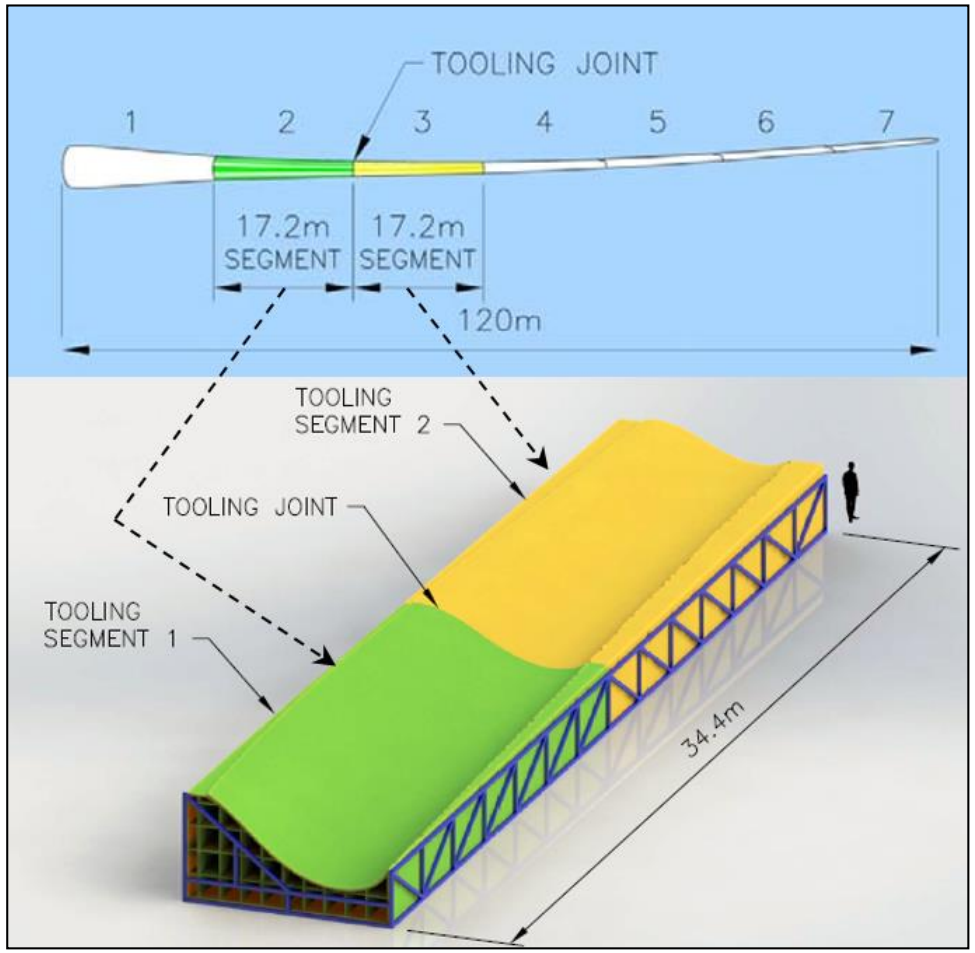
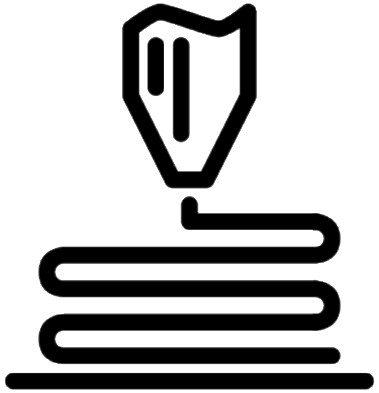
Defining the Future of AM

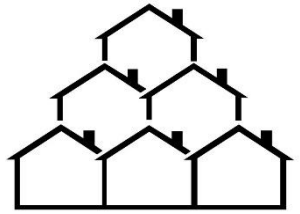
2010 | 2014 | 2018 | 2022

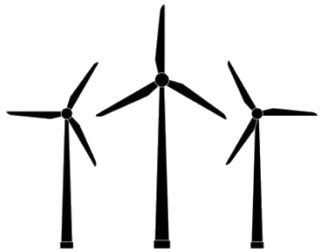
20 lb/hr

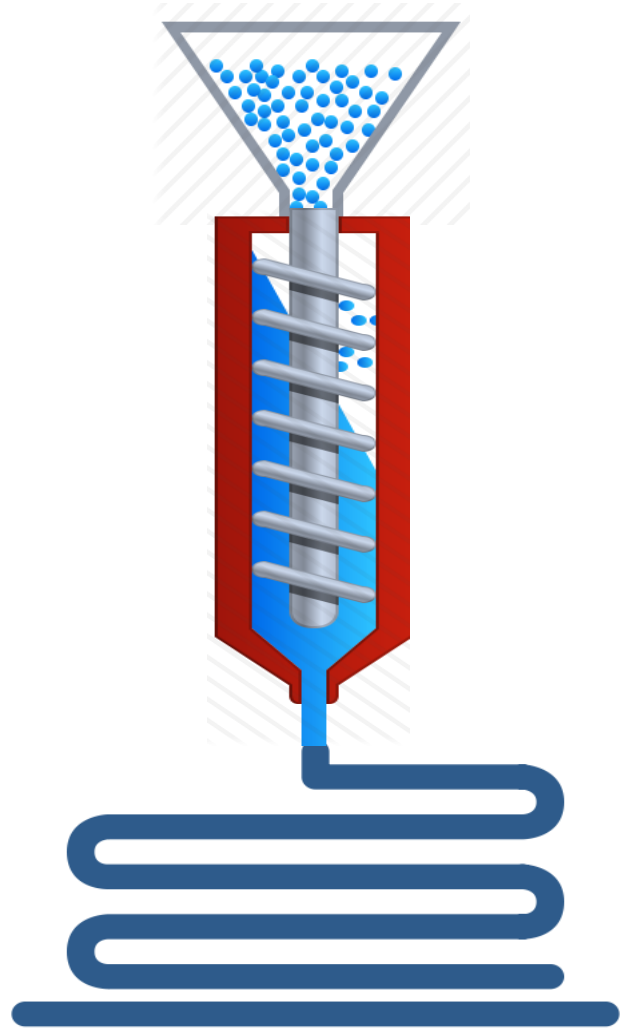




100 lb/hr







500 lb/hr +

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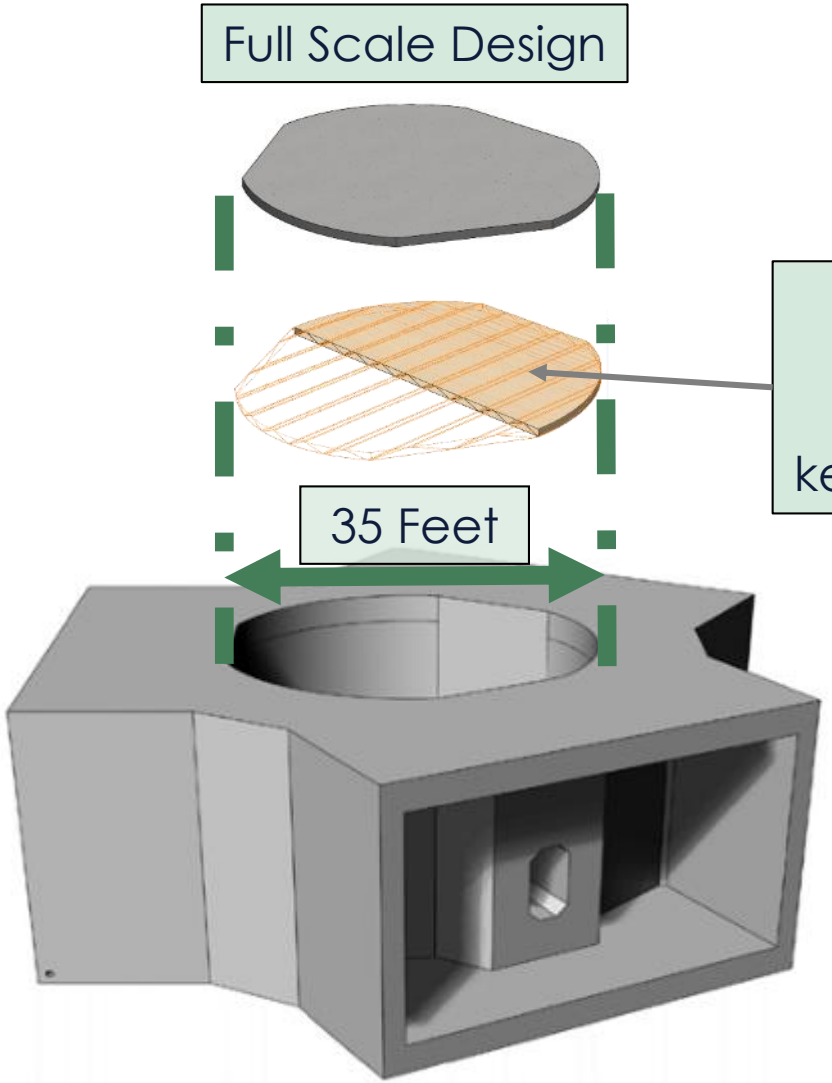
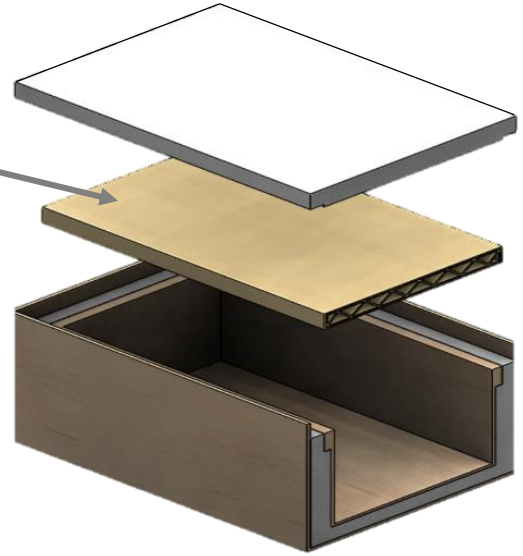
3D Printing Offshore Wind hull formwork



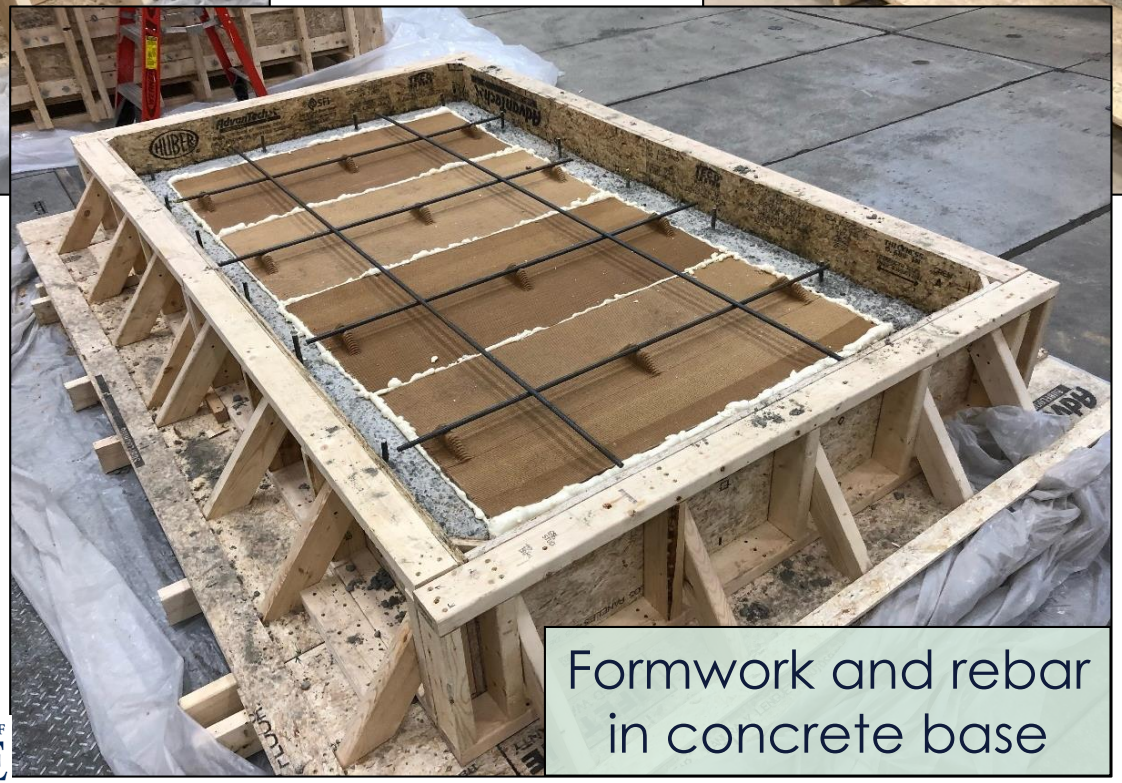
Formwork supports concrete keystone cap



3D Printing Concrete Formwork

Concrete base

Final concrete "keystone"



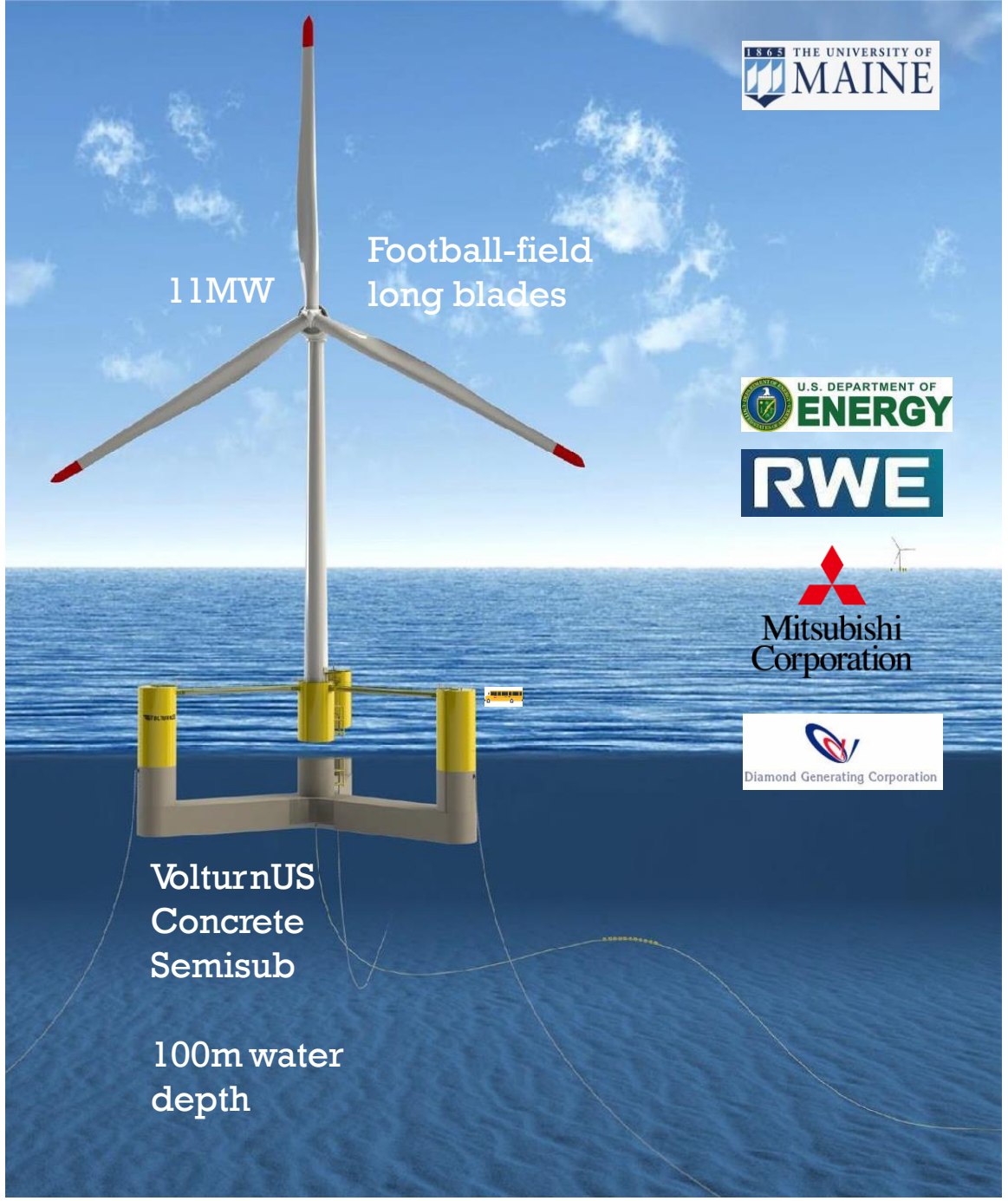
Formwork and rebar in concrete base

Printing stay-in-place formwork presents a **26.7%** cost saving considering material, time, labor, etc.

This formwork eliminates a 1.75" deflection as compared to traditional formwork. This represents a **14.6%** saving in concrete usage.

New England Aqua Ventus I

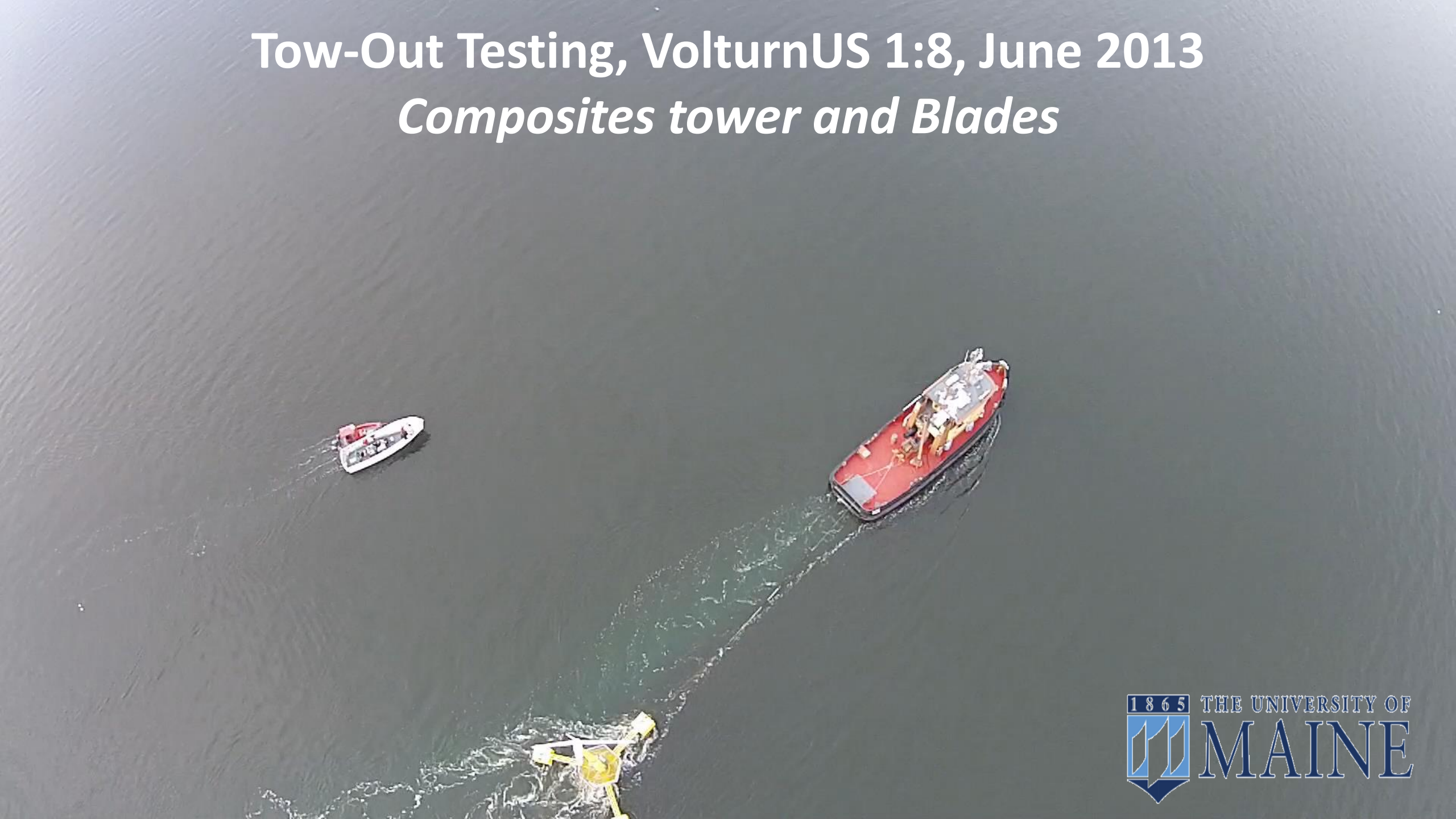
1. University of Maine VolturnUS Concrete semisubmersible design, has 60 patents
2. US DOE Advanced Technology Demonstration Program for Offshore Wind
3. RWE & Mitsubishi-DGC to invest $100 m
4. Monhegan Island, Maine
5. Start construction 2022, COD 2023/24



Dr. Habib J. Dagher, PE, Exec. Director hd@maine.edu

Tow-Out Testing, VolturnUS 1:8, June 2013

Composites tower and Blades



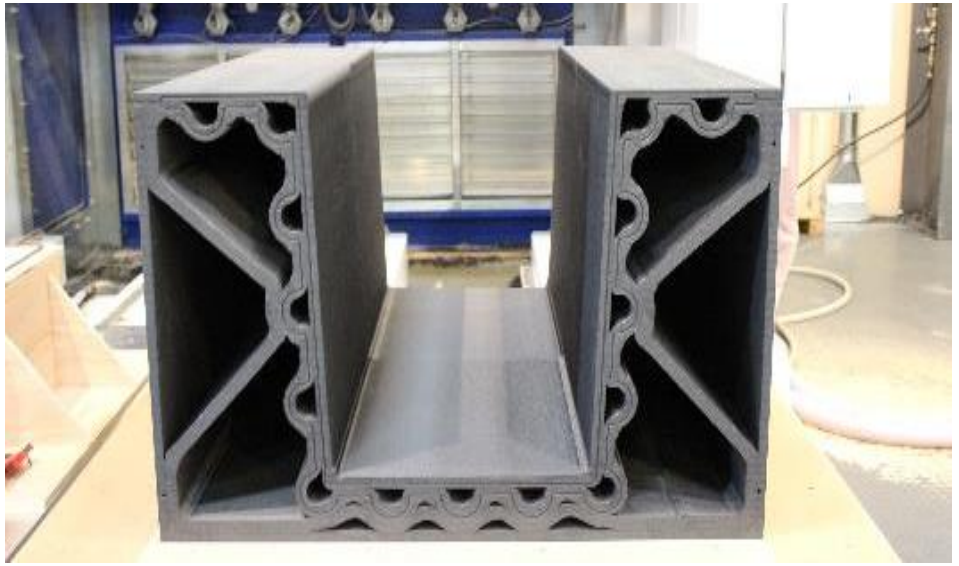
1865 THE UNIVERSITY OF MAINE

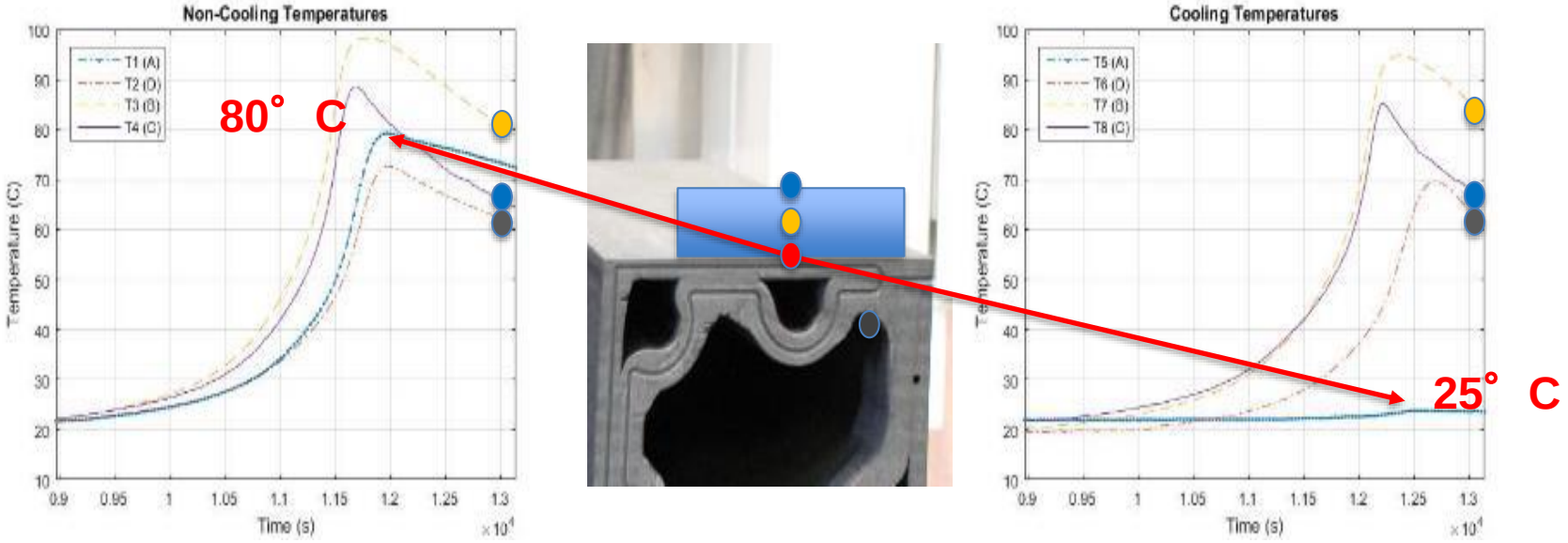
50-Year
Return Period Storm

THE UNIVERSITY OF MAINE

Integrated Heating Cooling

- Integral Cooling Channels
- Reduced Mold Surface Temperature 80°C → 25°C
- Could also be used for in mold post curing





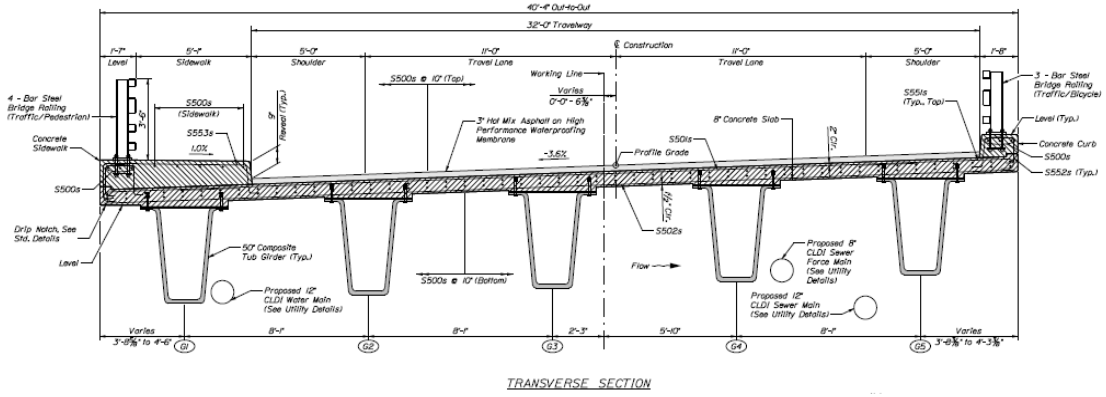
Bridge Girder Mold

Girder & Formwork

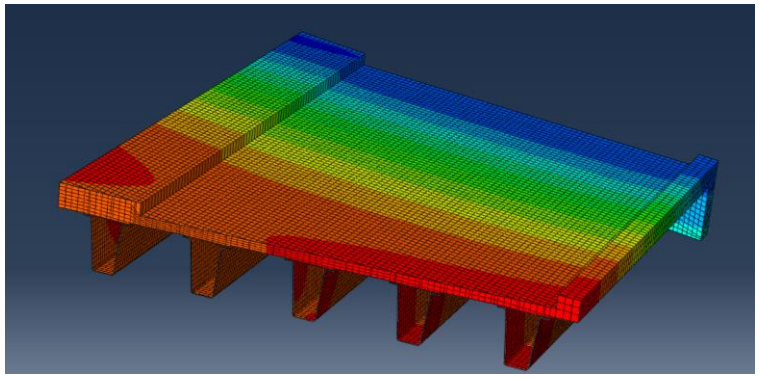
3D Printed Formwork

Bridge Girder

Tub Girder Bridge Construction



TRANSVERSE SECTION



75’ Composite Girder

Bridge Construction Oct 2020

The Grist-Mill Bridge

US Rte. 1 in Hampden, Maine
75’ span length , 40’-4” out-to-out width

Grist Mill Bridge Construction

Precision Manufacturing of Large Wind Blade Tools

Recap

- Hub and Spoke
- Cellulose AM feedstock opportunities and challenges
- Tech roadmap
- Funding for industry collaborations
- Applications: Boatbuilding, Offshore wind, formwork, bridges, culverts, wind blade tooling