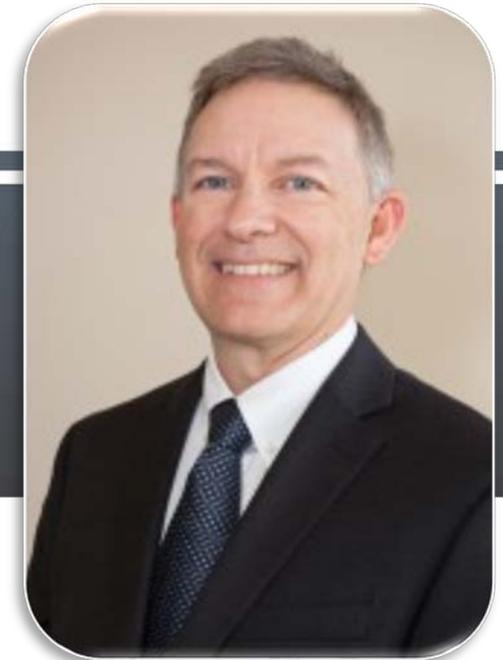




John A Hopkins
Sr. Project Controls Manager
IACMI



Institute for **ADVANCED**
Composites Manufacturing
INNOVATION



IACMI RD&D Projects Update

Institute for **ADVANCED**
Composites Manufacturing
INNOVATION

John A. Hopkins
Sr. Project Controls Manager

July 27, 2016

IACMI Proposal and Project Summary

- Four projects underway
- Three projects anticipated August Start
- Two enterprise proposals anticipated in August/September
- Three projects in contracting
- Four proposals in review

Projects - Underway

Project	Proposal Title	Partners	TA	Status
3.2	Optimized Carbon Fiber Production to Enable High Volume Manufacturing of Lightweight Automotive Components	Ford Dow, DowAksa, MSU, ORNL, Purdue, UT, UK, VU	V M&P DMS	In-line NDE & Benchmarking
3.3	Rapid Carbon Fiber Prepreg Molding Technology for Automobile Structural Parts (SEAHAWKS)	Toray Zoltek, Reichhold, Janicki, Globe Machine, CRTC, ACMA, MSU	V	Sample prep/delivery Monthly project meetings
3.4	Thermoplastic Composite Parts Manufacturing Enabling high Volumes, Low Cost, Reduced Weight with Design Flexibility	DuPont , Fibrtec Purdue	V DMS	8/1 kick-off
4.2	Thermoplastic Composite Development for Wind Turbine Blades	Johns Manville NREL, CSM, TPI, Arkema, UT, VU, Purdue	W M&P DMS	Sample prep planning Bi-weekly project meetings

Open Call Projects – In Contracting

Proposal Title	Partners	TA	Status
Enabling Composite Processing through the OEM Assembly Line	PPG Ford, MSU	V	Finalizing Project Agreement
Low-Cost, Energy-Efficient Crashworthy Hybrids	PPG A&P, Dow, MSU	V	Finalizing Project Agreement
Reclaimed Carbon Fiber Reinforced Automotive Part using 3-DEP Preforms and Preform Tooling using Reclaimed Carbon Fiber and MDF's Additive Manufacturing Process	Materials Innovation Technologies ORNL	V M&P	Finalizing Project Agreement
BAAM Materials Development and Reinforcement with Advanced Composites	Local Motors ORNL	V M&P	In Execution
Low Cost Pultruded Carbon Fiber Reinforced Polymer (CFRP) Composites for Spar Caps	TPI DowAksa, Strongwell, ORNL, UTK, VU, NREL, (GE)	Wind M&P	Drafting Project Agreement

Open Call Projects In Review

Proposal Title	Partners	TA	Status
Development of NDE/NDT Tools for High-Volume, High-Speed Inspection of CFRP Structures in Automotive Manufacturing	American Chemistry Council Plasan, VU	V	IACMI Tech SLT
Recycling Carbon Fiber Composite Aircraft Parts and Product Development from Reclaimed Fibers	Universal Asset Management Adherent, Local Motors, UTK, ORNL	M&P	IACMI Tech SLT
Chopped Fiber – Automotive Component	Asahi Kasei Magna, FCA, Ford, UTK, MSU, ORNL	V M&P	TAB review (8/1)
Prepreg and Automated Layup for CGS	DuPont Steelhead, CPC, UDRI	CGS	TAB Review (8/1)

Project Updates

4.2 Thermoplastic Composite Development for Wind Turbine Blades

John Dorgan, Ph.D., Colorado School of Mines

BAAM Materials Development and Reinforcement with Advanced Composites

Charles Hill, Local Motors

Reclaimed Carbon Fiber Reinforced Automotive Part using 3-DEP Preforms and Preform Tooling using Reclaimed Carbon Fiber and MDF's Additive Manufacturing Process

Jim Stike, Materials Innovation Technologies

3.3 Seahawks - Rapid Carbon Fiber Prepreg Molding Technology for Automobile Structural Parts

Felix Nguyen, Ph.D., Toray Composites (NA)



Thermoplastic Composite Development for Wind Turbine Blades

NREL: Derek Berry and David Snowberg,
TPI Composites: Steven Nolet

CSM: John Dorgan, Yasuhito Suzuki, Dylan Cousins, Aaron Frary, David Ruehle

JohnsMaville: Jawed Asrar, Klaus Gleich, Mingfu Zhang, Michael Block

Arkema Chemical: Dana Swan, Robert Barsotti, Mark Aubart

Colorado OEDIT: Katie Woslager

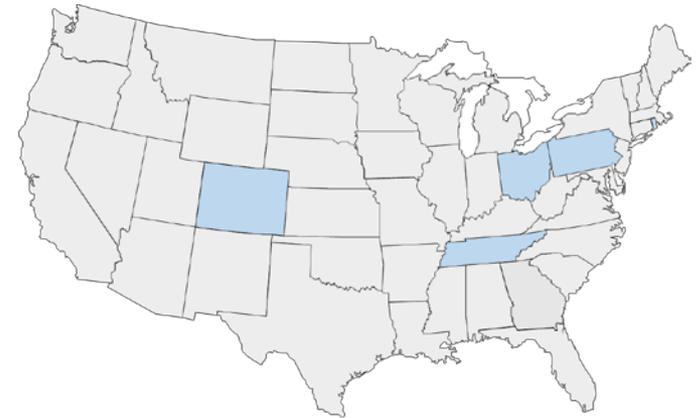
Institute for **ADVANCED**

Composites Manufacturing

INNOVATION

Thermoplastic Composite Development for Wind Turbine Blades

- **Challenge:** Fiber reinforced polymer composites are the material of choice for large scale wind turbine components, but challenges in *manufacturing costs*, *performance*, and *recyclability* are limiting.
- **Approach:** Development of thermoplastic materials to *lower production costs* and improve recyclability of wind turbine blades and applicability to components *demonstrated at large scale*.
- **Impact:** Cost reductions in composite materials for wind turbine blades will enable lower cost of electricity; property improvements enable larger scale and increased efficiency.
- **Partners:** NREL, TPI, Johns Manville, Colorado School of Mines. Arkema joined in BP2 (new partners expected in BP3).
 - **Cross-cutting partnering** includes NDE team from Vanderbilt, and ORNL/University of Tennessee.
 - **Simulation tool development** in conjunction with Purdue group and Convergent



- Wind, Project 4.2
- TRL/MRL Impact: from 3 to 4

Thermoplastic Composites – Accomplishments

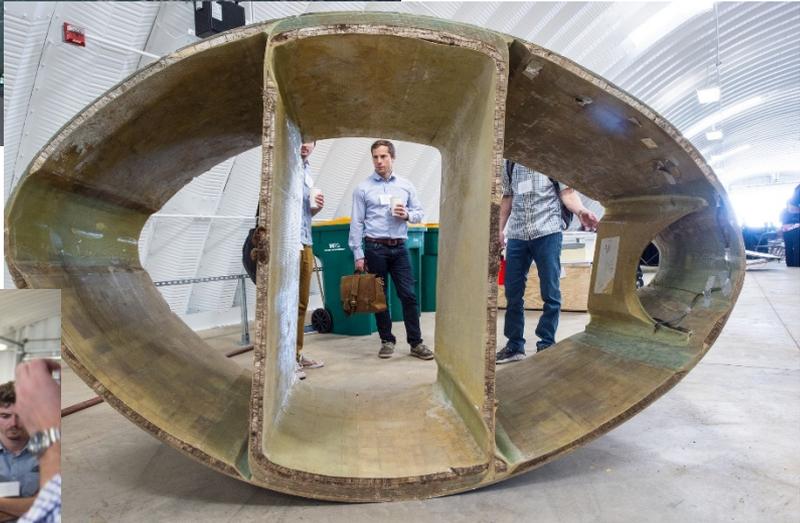
- **Added Arkema** as major new corporate partner
 - Work plan expanded to include innovative *Elium*TM system
- Commissioned **two new facilities**
 - VARTM lab at Colorado School of Mines (CSM) (Fabricated proof of concept panels at CSM, JohnsManville, and Arkema).
 - Blade component manufacture at NREL Wind Technology Center (thick root section mold arriving soon – demonstration at scale)
- **Property database** creation
 - Collected rheological data for liquid precursor and curing resin
 - Established testing protocols and plan for comparison to thermosets
- *Cross-cutting: Modeling and Simulation*
 - **Developed chemical kinetics / heat transfer model** and initiated transfer to Convergent for incorporation into *Raven* process simulator.
 - *Cross-cutting: Non Destructive Evaluation (NDE)*
 - **Established thermal imaging / emission FTIR**

VARTM Lab at CSM



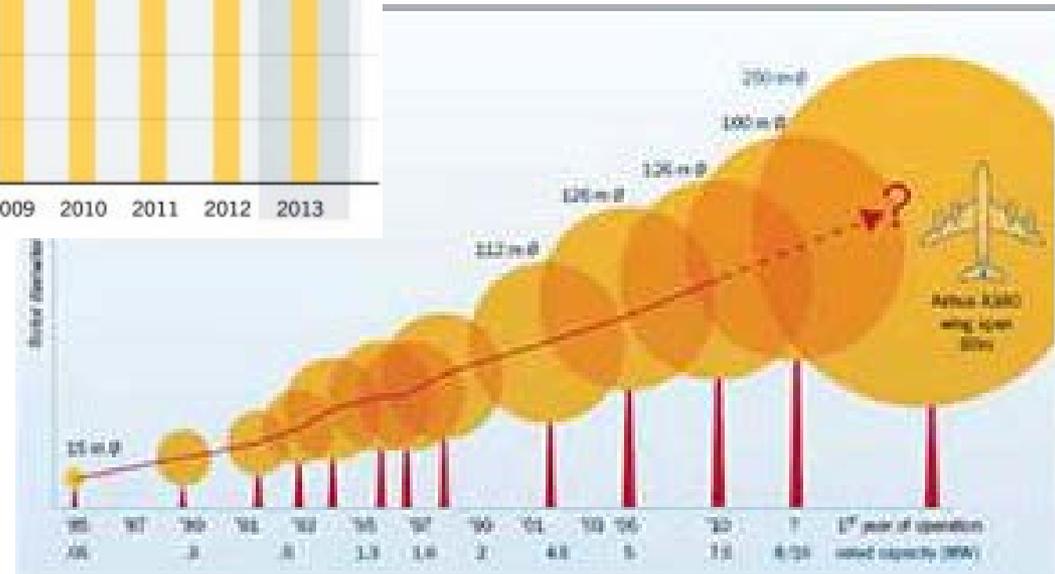
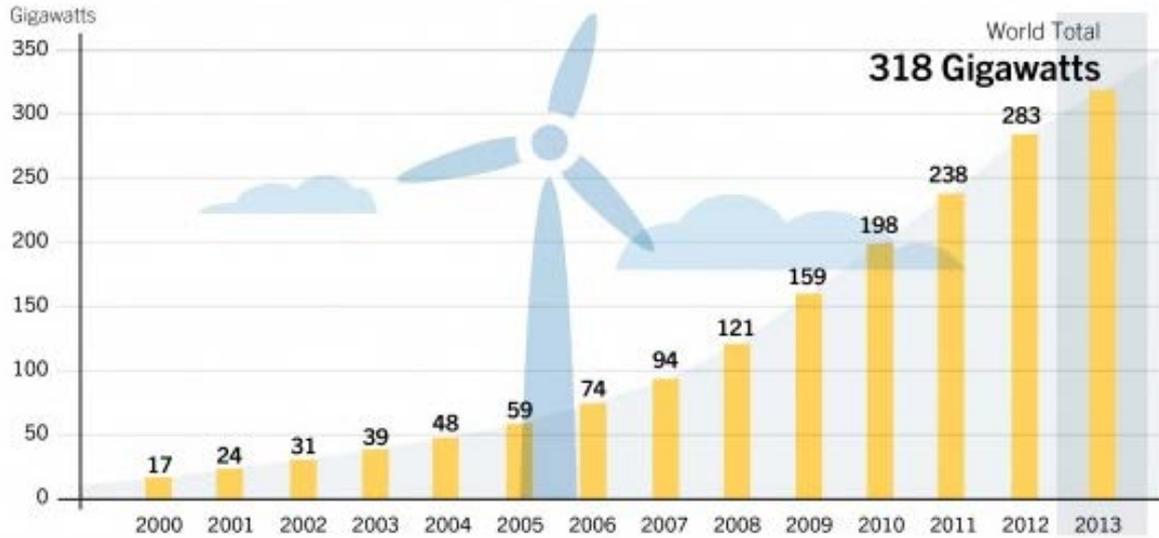
- Complementary facilities at Johns Manville in Littleton, Colorado (*just 15 miles away*).

Demonstration scale at NREL



Wind Turbines - More and Bigger

Wind Power Total World Capacity, 2000–2013



A 60m blade weighs 10 tons and is 30 wt% polymer resin.

Wind Turbines – Program Goals

- Increase **jobs** for American workers.
- Increase domestic **production capacity**.
- **Reduce life cycle** energy use and associated greenhouse gas emissions. Double the energy productivity of fiber reinforced polymer composite manufacturing.
- **Demonstrate at scale** reduced embodied energy and associated greenhouse gas emissions.
- Demonstrate at scale **greater than 80% recyclability**.

Thermoplastic based composites
enable reaching these goals!

Why Thermoplastics?

Plastics are characterized according to their response to temperature:

Thermoplastics - soften and flow upon heating:

- T_g - Glass Transition Temperature
(beginning of chain motion over several segments)
- T_m - Melting Temperature (chains can self-diffuse)
(for semi-crystalline polymers)

Some thermoplastics are amorphous glasses without melting temperatures.

Thermosets - rigid until thermal decomposition

Epoxies, unsaturated polyesters, and other
network forming materials that are used today

Why Thermoplastics?



End-of-life composite part or production waste

Grinding



20 – 40%

Compounding (ABS, PLA, PMMA, etc.)



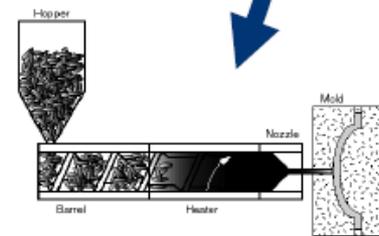
Short fiber compound

PROPERTIES

	Commercial compound ABS-GF20	ABS + 40% recycled Elium®
Injection	Same conditions	
Stiffness	4.9 GPa	6.9 GPa
Strength	69 MPa	76 MPa
Impact Charpy	13 kJ/m ²	22 kJ/m ²



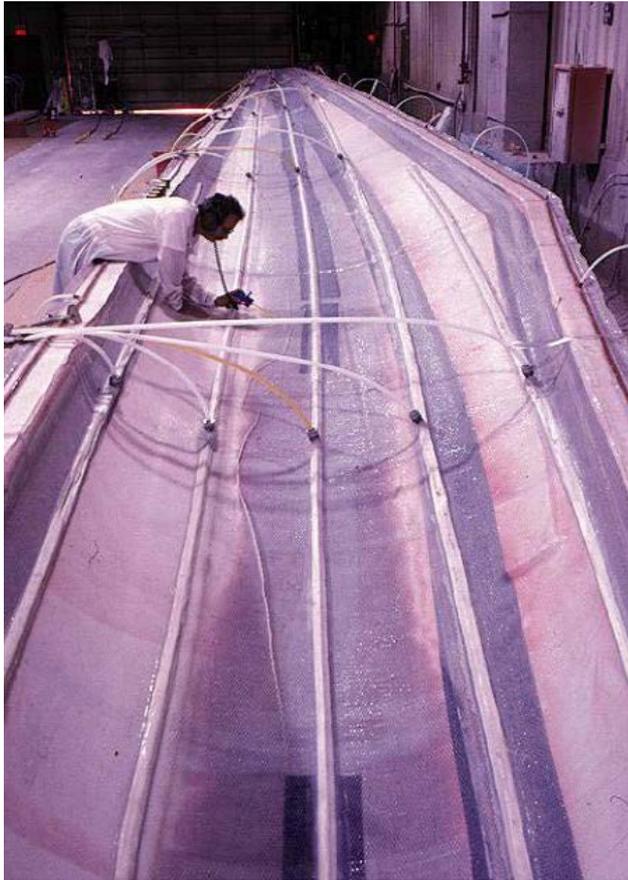
NEW Composite part



Injection molding of short fiber compound

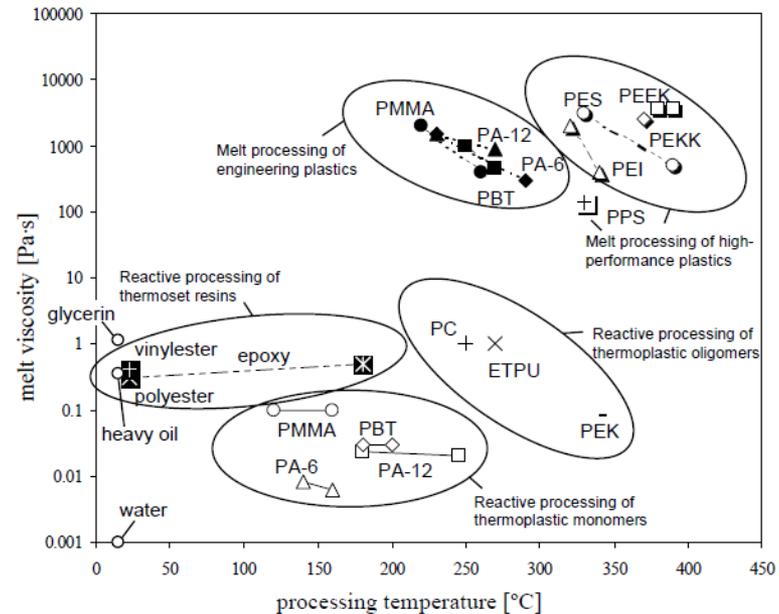
Improvement of short fiber ABS compound when recycling ELIUM® composites.

Thermoplastic infusion



VARTM – Vacuum Assisted Resin Transfer Molding.

Low viscosity resins infused and then *cured* in mold / autoclave.



Not injecting high viscosity preformed polymers!

The Institute for Advanced Composites Manufacturing Innovation

Thermoplastic infusion

Elium[®] resins for composites

Product range

Elium[®] is the first liquid thermoplastic resin designed for manufacturing composite parts with mechanical properties similar to thermosetting. The major advantage of Elium[®] is it acts like a thermoplastic, which means it is uniquely designed for thermoforming, recycling and welding.

ELIUM[®]
BY ARKEMA

Description

Products

Resources

News & events

Contact

Properties

- **30 to 50% lighter** than the same parts made from **steel** with the same resistance
- Perfect for **complex design forms**
- Seamlessly blends with **glass or carbon fibers**
- Compatible with **conventional thermosetting resin transformation technologies** (Resin Transfer Moulding, Infusion, Flex-molding).
- **Styrene free** compared to unsaturated polyesters
- Parts **easily thermoformed and recycled** with comparable mechanical performance for epoxy parts
- **Exceptional post-thermoforming** (welding and gluing)
- **Cost less to manufacture** compared to other thermoplastic technologies:
 - Conventional thermoset resin processes
 - Transformation at room temperature
 - No organo-sheets.

“Acrylate based”
- Dana Swan

Johns Manville Innovation

(12) **United States Patent** (10) **Patent No.:** **US 8,378,094 B2**
Shooshtari et al. (45) **Date of Patent:** **Feb. 19, 2013**

(54) **POLYMERIZATION INITIATORS FOR FIBER-REINFORCED POLYMER COMPOSITES AND MATERIALS MADE FROM THE COMPOSITES**
 4,697,009 A 9/1987 Deschler et al.
 5,782,908 A 7/1998 Cahalan et al.
 5,864,007 A 1/1999 Schmid et al.
 6,013,855 A 1/2000 McPherson et al.

(75) Inventors: **Kiarash Alavi Shooshtari**, Litt (US); **Jawed Asrar**, Englewood (US); **Rajappa Tadepalli**, Littl (US); **Thomas Burghardt**, Par (US); **Klaus Friedrich Gleich**, Highlands Ranch, CO (US) (12) **United States Patent** (10) **Patent No.:** **US 8,293,322 B2**
Burghardt et al. (45) **Date of Patent:** **Oct. 23, 2012**

(73) Assignee: **Johns Manville**, Denver, CO (1) (54) **SURFACES CONTAINING COUPLING ACTIVATOR COMPOUNDS AND REINFORCED RESINS PRODUCED THEREFROM**
 4,697,009 A 9/1987 Deschler et al.
 5,096,644 A * 3/1992 Endo et al. 264/137
 5,132,342 A * 7/1992 Chillous 523/513
 5,240,974 A * 8/1993 Lechner et al. 523/214
 5,782,908 A 7/1998 Calahan et al.
 5,864,007 A 1/1999 Schmid et al.
 6,013,855 A 1/2000 McPherson et al.
 6,358,557 B1 3/2002 Wang et al.
 6,579,965 B2 6/2003 Hoogen et al.
 2003/0096904 A1 5/2003 Hakuta et al.
 2007/0072199 A1 3/2007 Levicky et al.

(19) **United States**
 (12) **Patent Application Publication** (10) **Pub. No.:** **US 2010/0305269 A1**
Gleich et al. (43) **Pub. Date:** **Dec. 2, 2010**

FOREIGN PATENT DOCUMENTS

08-291186 11/1996
 2003084583 10/2003

(54) **METHODS AND SYSTEMS FOR MAKING REINFORCED THERMOPLASTIC COMPOSITES, AND THE PRODUCTS** Publication Classification
 (51) **Int. Cl.**
C08K 3/40 (2006.01)
B29C 33/02 (2006.01)
B01J 19/00 (2006.01)
 (52) **U.S. Cl.** **524/606; 264/240; 422/138**
 (57) **ABSTRACT**

(75) Inventors: **Klaus Friedrich Gleich**, Highlands Ranch, CO (US); **Jawed Asrar**, Englewood, CO (US); **Thomas E. Burghardt**, Parker, CO (US); **Rajappa Tadepalli**, Highlands Ranch, CO (US)

Correspondence Address:

JOHNS MANVILLE

Various methods and systems of making inorganic fiber/flake reinforced composites having a thermoplastic matrix are dis-

Johns Manville Innovation

(19) **United States**

(12) **Patent Application Publication**
Tadepalli et al.

(10) **Pub. No.: US 2011/0021737 A1**

(43) **Pub. Date: Jan. 27, 2011**

(54) **FIBER-REINFORCED COMPOSITE ARTICLES MADE FROM FIBERS HAVING COUPLING-INITIATOR COMPOUNDS AND METHODS OF MAKING THE ARTICLES**

(76) Inventors: **Rajappa Tadepalli**, Littleton, CO (US); **Jawed Asrar**, Englewood, CO (US); **Klaus Friedrich Gleich**, Highlands Ranch, CO (US)

Publication Classification

- (51) **Int. Cl.**
C08G 77/04 (2006.01)
B29C 70/30 (2006.01)
- (52) **U.S. Cl.** **528/26; 264/258; 528/27**

Correspondence Address:

JOHNS MANVILLE
10100 WEST UTE AVENUE, PO BOX 625005
LITTLETON, CO 80162-5005 (US)

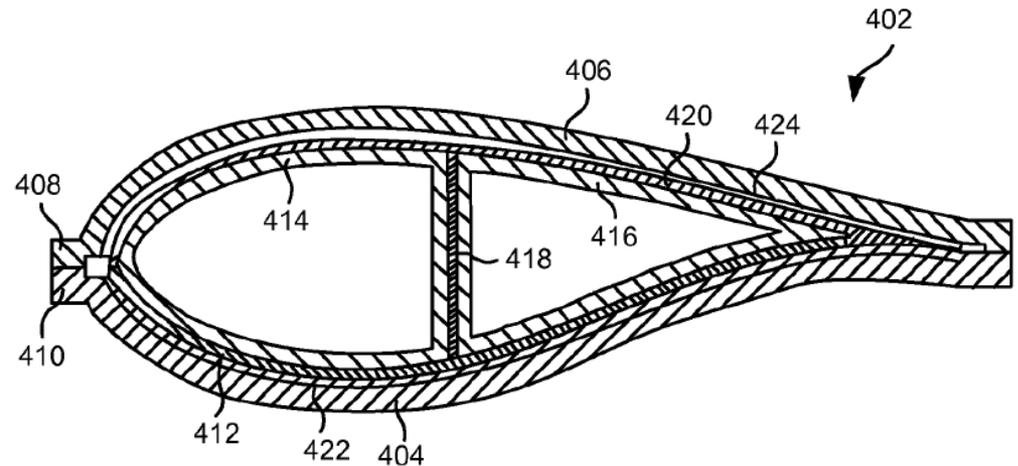
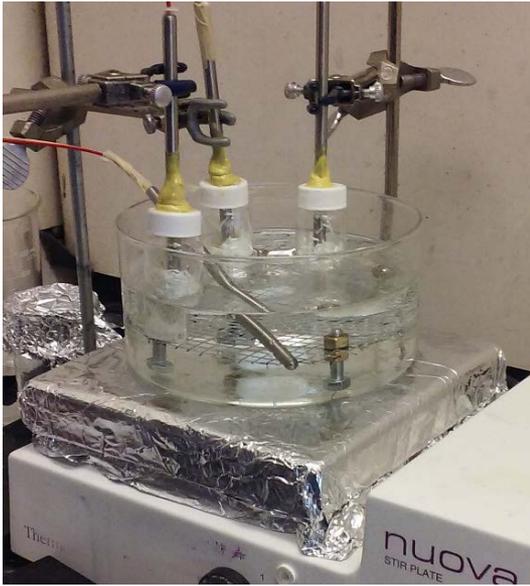


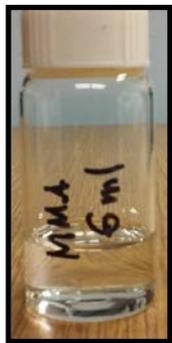
Fig. 4

TRL is suitable for NNMI

Experiments at CSM



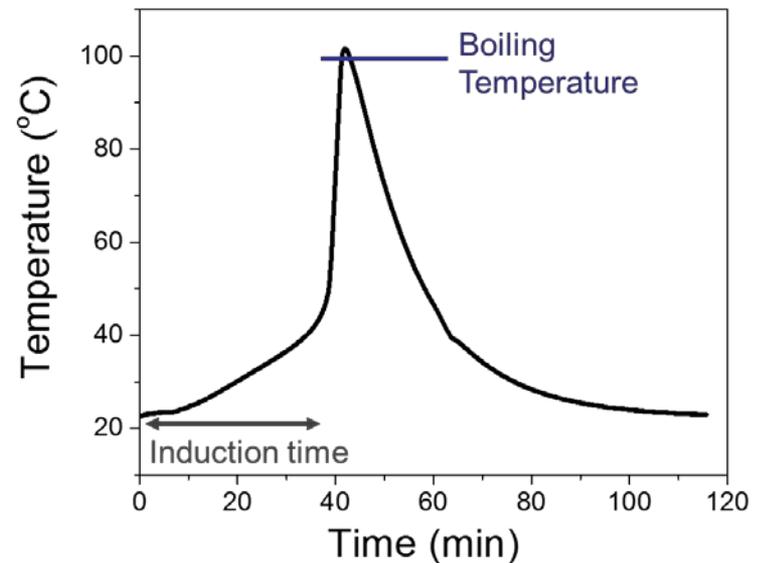
- Samples of methylmethacrylate (MMA) monomer immersed in constant T bath.
- J-Type thermocouples with a data logger.



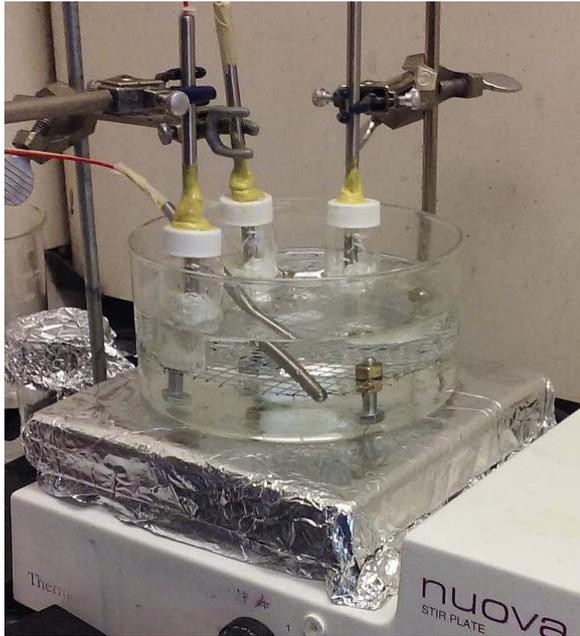
Wall temperature
25 °C



2 hour cure time



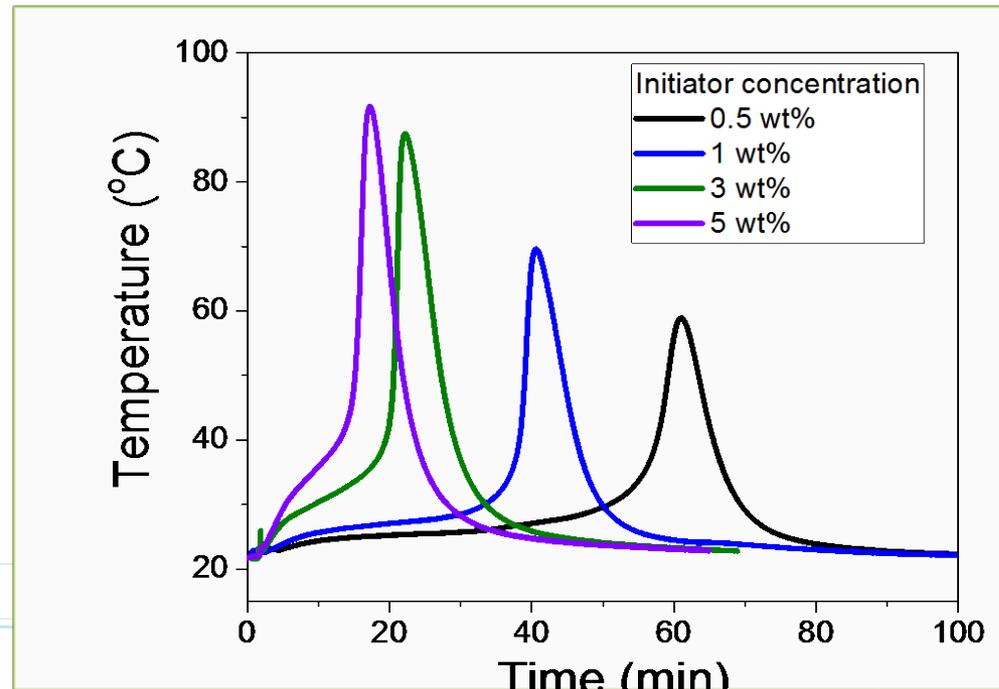
Experiments at CSM



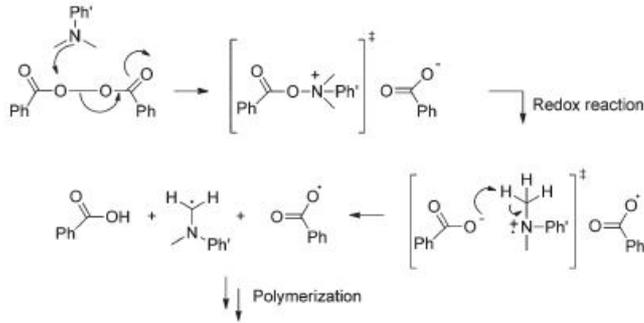
Elium has a **lower exotherm**.

Initiator is analogous to hardener / curative in epoxy systems.

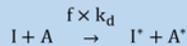
Less initiator means slower reaction and lower peak temperatures due to increased time for heat transfer



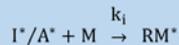
Cross-Cutting : Model Development



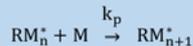
Decomposition:



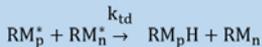
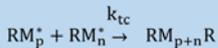
Initiation:



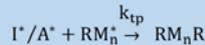
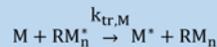
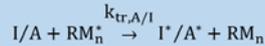
Propagation:



Termination:



Side Reactions:



I = initiator, A = amine,
R = decomposition component,
M = monomer.

1. Concentration of the initiator

$$\frac{d[I]}{dt} = -f \cdot k_d \cdot [I][A] - k_{tr,I} \cdot [I][RM_n^*]$$

2. Concentration of the Amine

$$\frac{d[A]}{dt} = -f \cdot k_d \cdot [I][A] - k_{tr,A} \cdot [A][RM_n^*]$$

3. Concentration of the initiator radicals

$$\frac{d[I^*]}{dt} = f \cdot k_d \cdot [I][A] - k_{i,I} \cdot [I^*][M] - k_{tp} \cdot [I^*][RM_n^*] + k_{tr,I} \cdot [I][RM_n^*]$$

4. Concentration of the Amine radicals

$$\frac{d[A^*]}{dt} = f \cdot k_d \cdot [I][A] - k_{i,A} \cdot [A^*][M] - k_{tp} \cdot [A^*][RM_n^*] + k_{tr,A} \cdot [A][RM_n^*]$$

5. Concentration of the monomer

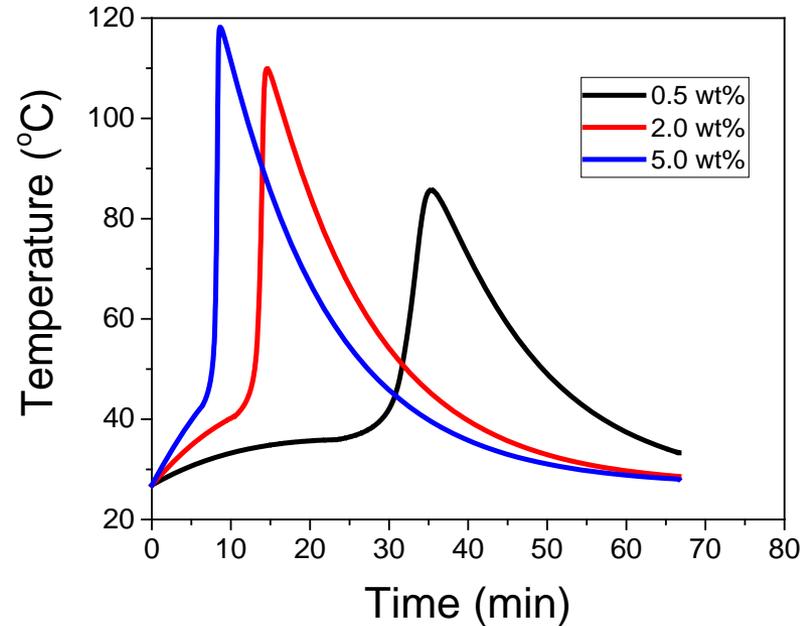
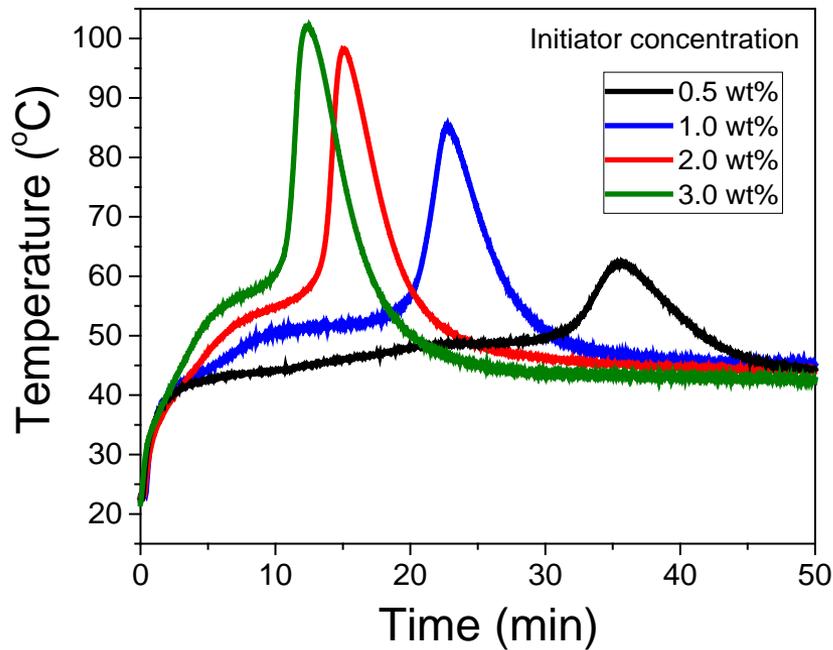
$$\frac{d[M]}{dt} = -(k_{i,I}[I^*] + k_{i,A}[A^*])[M] - k_p \cdot [RM_n^*][M] - k_{tr,M} \cdot [M][RM_n^*]$$

6. Concentration of the polymer radicals

$$\frac{d[P^*]}{dt} = (k_{i,I}[I^*] + k_{i,A}[A^*])[M] - (k_{tc} + k_{td}) \cdot [P^*]^2 - (k_{tr,I}[I] + k_{tr,A}[A])[P^*] - k_{tr,M} \cdot [P^*][M] - (k_{tp}[I^*] + k_{tp}[A^*])[P^*]$$

Chemical kinetics coupled to heat transfer and including “gel effect” due to diffusional limitations

Cross-Cutting: Model Development



Qualitative description based on literature values

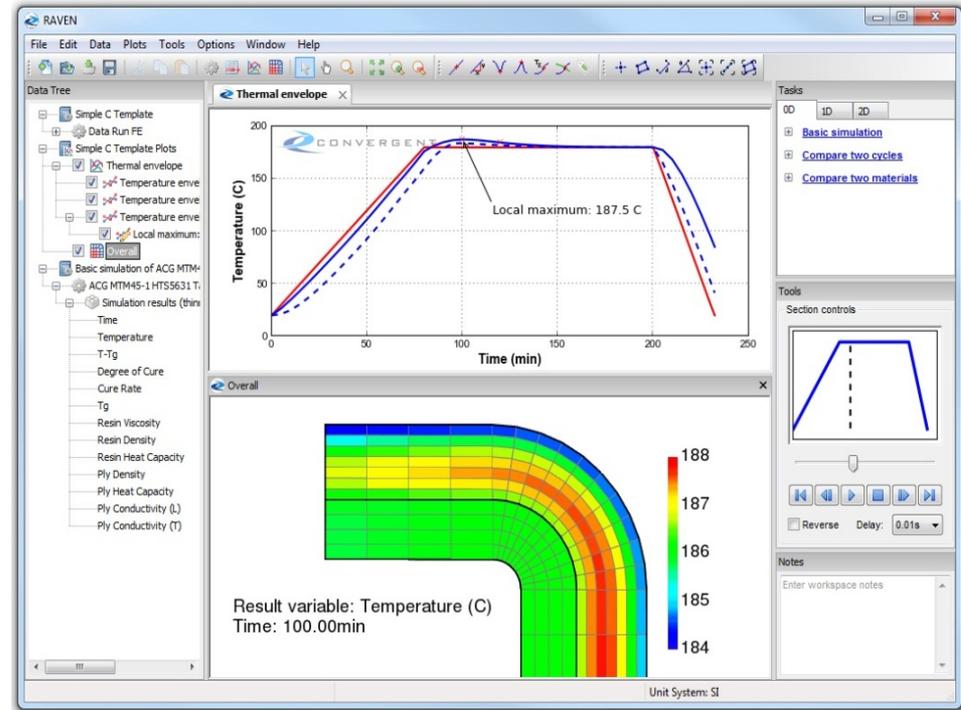
Determining parameter set for quantitative description

Process Modeling with RAVEN

RAVEN is a desktop composites processing analysis program that allows users to **design**, **optimize**, and **troubleshoot** processing of composites.

RAVEN is used for:

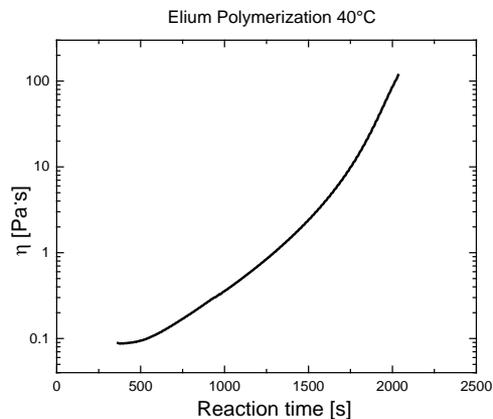
- Cure cycle optimization
- Thermal profiling
- Troubleshooting



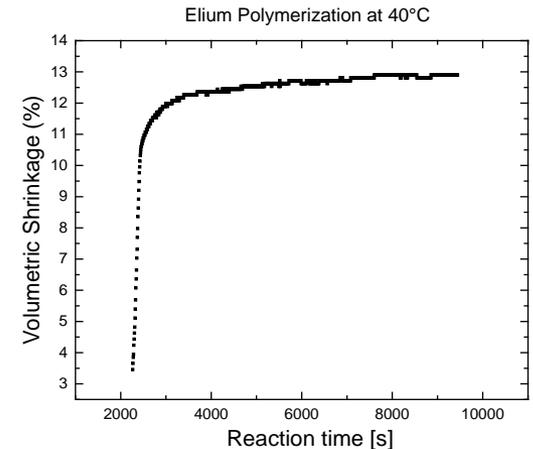
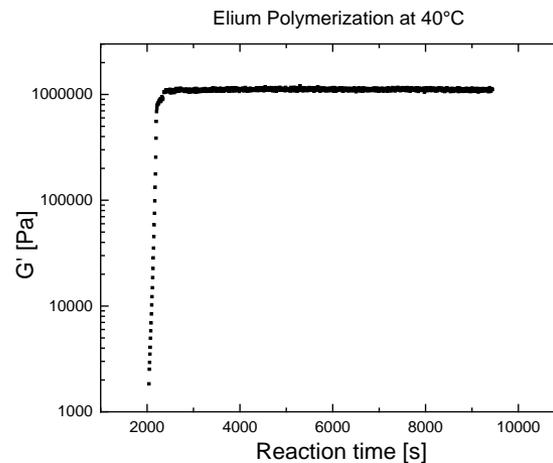
Rheology and shrinkage data for simulation

Elium reaction rheology experiments take place in two steps:

1) Measure the viscosity as a function of time at a constant shear rate of 100 1/s with the gap fixed at 1 mm:



2) When the torque on the geometry reaches a cutoff value, switch to an oscillatory measurement at 3.33 rad/s and allow the gap to change to produce an applied normal force of 0.5 N:

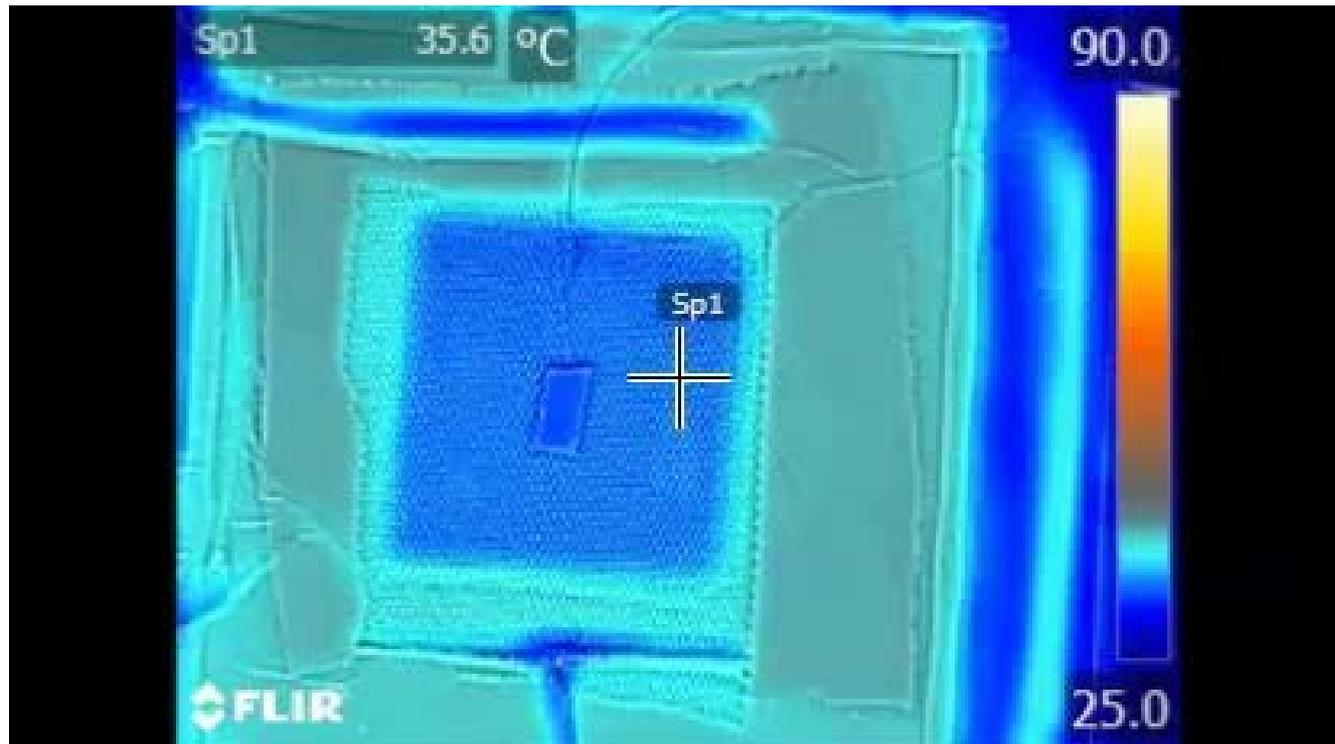


$$\varepsilon_v = \left[1 + \frac{1}{3} \left(\frac{h - h_0}{h_0} \right)^3 \right] - 1$$

h = gap height

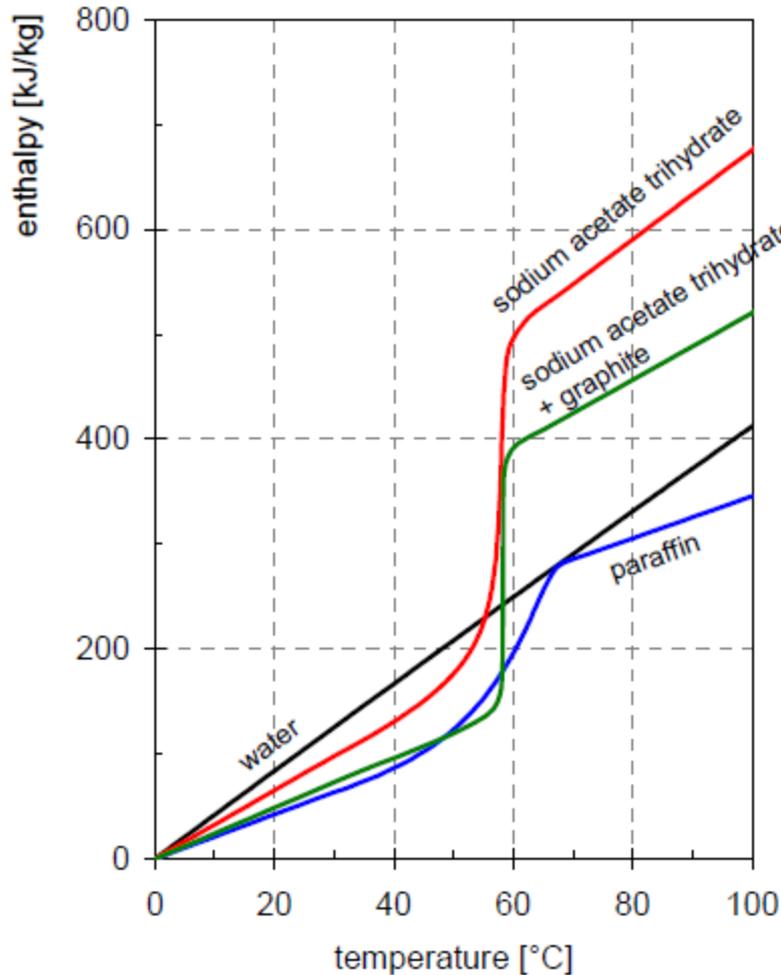
h_0 = initial gap height

Heat imaging during infusion



- Elium with 3 wt% initiator package
- 40 minutes time lapse
- Frame speed is 1 min or 30 s during rapid temperature change.

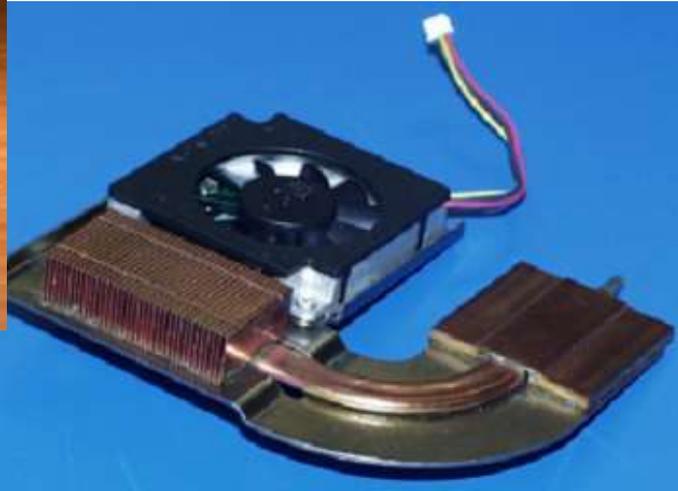
Phase Change Materials (PCMs)



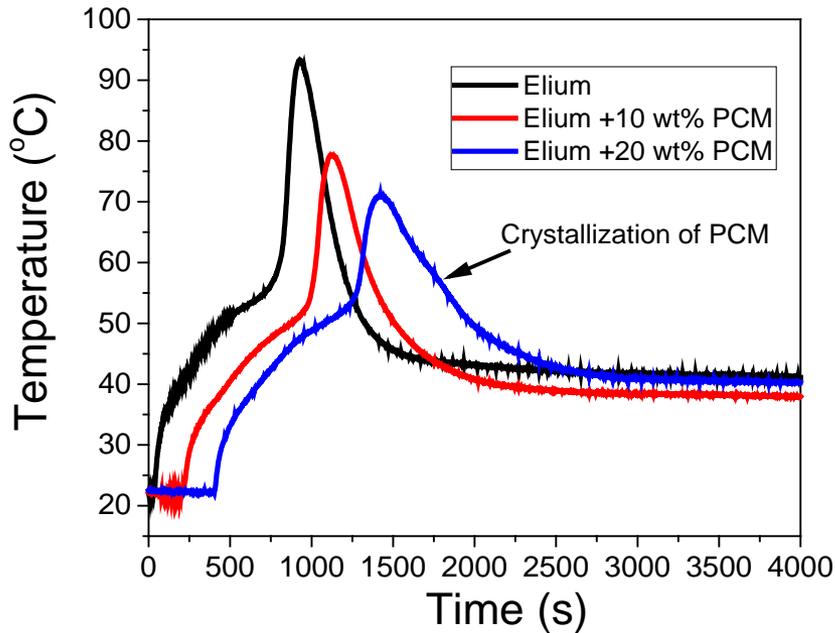
- Recall:
 - “**Sensible**” heat is energy to raise the T of a given phase (water in this graph).
 - “**Latent**” heat is the energy needed to change phases; to melt a crystal for example. This is more properly the “heat of fusion”.
 - ***Latent heats are much larger than sensible heats.***

Phase Change Materials (PCMs)

- PCMs have become widely used:
 - Domino Pizza “Heat Wave” bag
 - Every laptop has a “heat pipe” which uses liquid to gas vaporization
 - Outlast Technology (now part of CoorsTek) adopted NASA space suit technology to outdoor clothing.



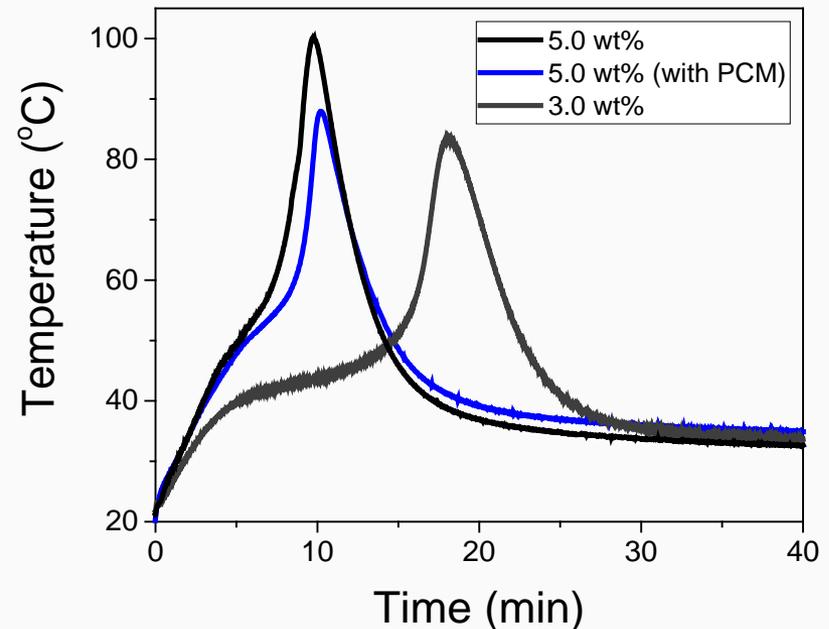
Effect of commercial PCMs on Elium™



Same initiator composition

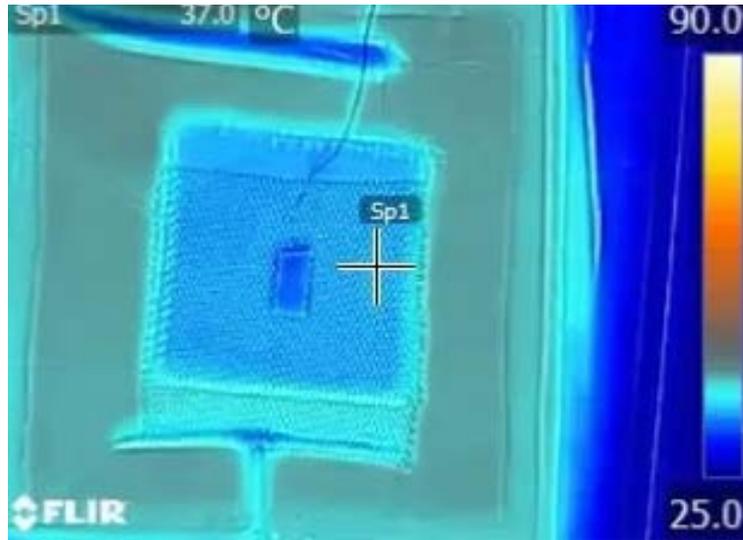


PCMs enable
shorter cycle times!



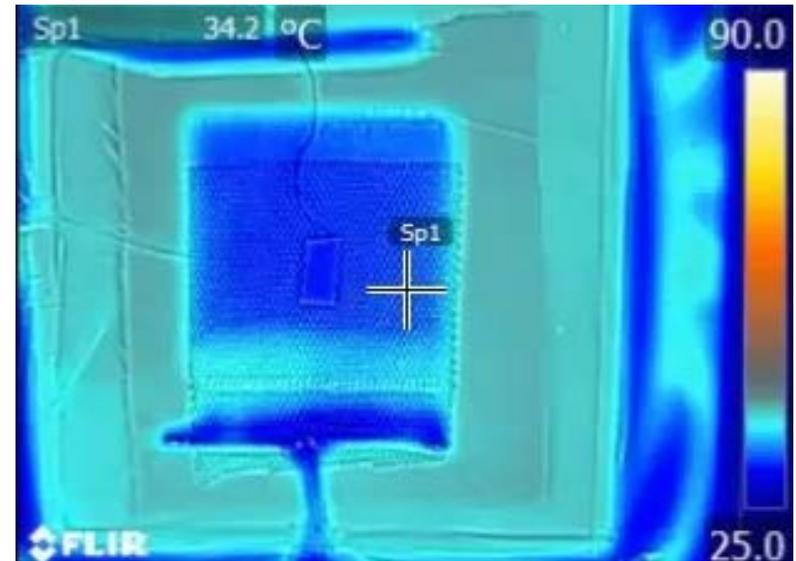
Heat imaging during infusion

Without PCM



$T_{\text{peak}} = 104 \text{ }^{\circ}\text{C}$

With PCM



$T_{\text{peak}} = 84 \text{ }^{\circ}\text{C}$

Slow motion during the curing reaction

NDE – cold spots reveal problems and in situ emission FTIR can provide cure information

Thermoplastic Composites Team

- **Met all budget period 1 milestones and on-track to meet all period 2 milestones**
- **Commissioned two new facilities**
 - VARTM lab at Colorado School of Mines (CSM)
 - Blade component manufacture at NREL
- **Property database creation**
 - Collected rheological data for liquid precursor and curing resin
 - Established testing protocols and plan for comparison to thermosets
- **Developed chemical kinetics / heat transfer model**
 - Initiated tech transfer to Convergent for *Raven* process simulator.
- **Developed NDE plan (Vanderbuilt / ORNL group)**
- **Demonstrated that PCMs can shorten cycle times**
- **Filed 1 patent, submitted 1 paper + 1 CAMX abstract, 2 more patents in preparation.**

Why Thermoplastics?

When “cured” ELIUM[®] resin remains *fully* thermoplastic!

- Allows for post-forming
- Excellent aesthetics; clarity and surface finish



Forming conditions

- ~200°C and 15 - 20 bar applied pressure (~250 PSI)
- Degree of draw and applied pressure are dependent on thickness and reinforcement type used in the part



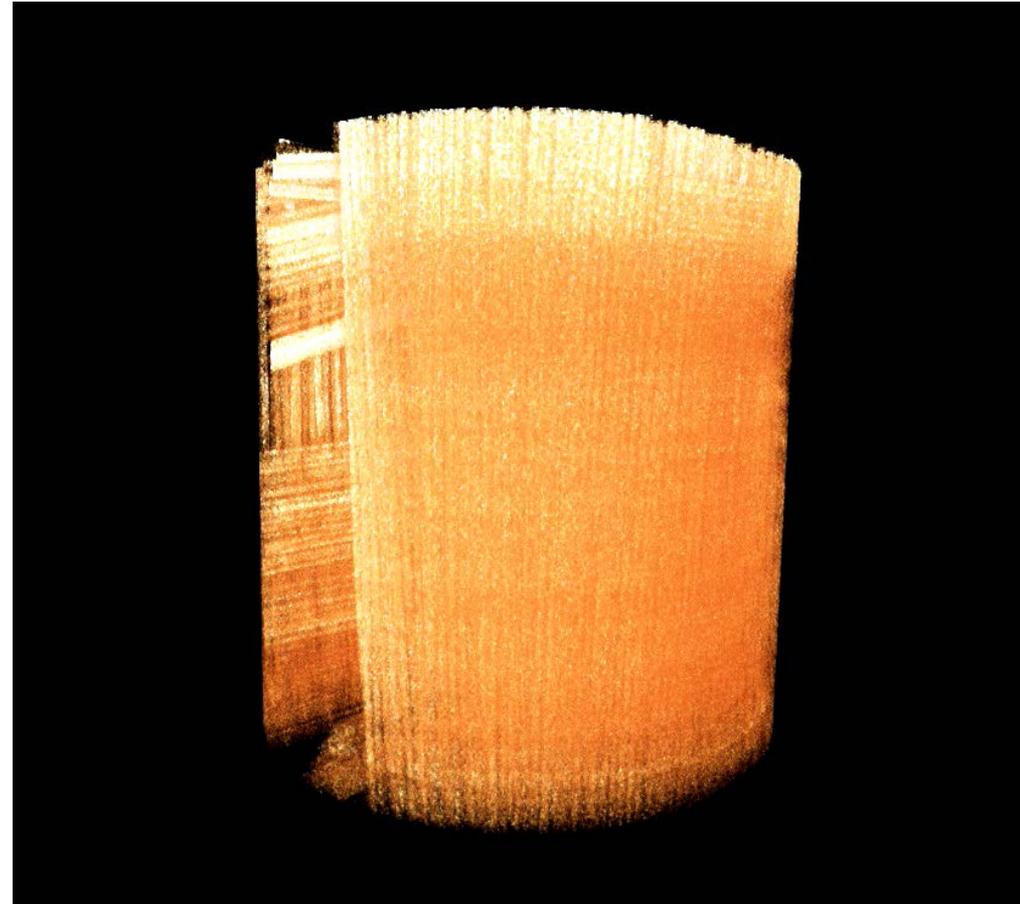
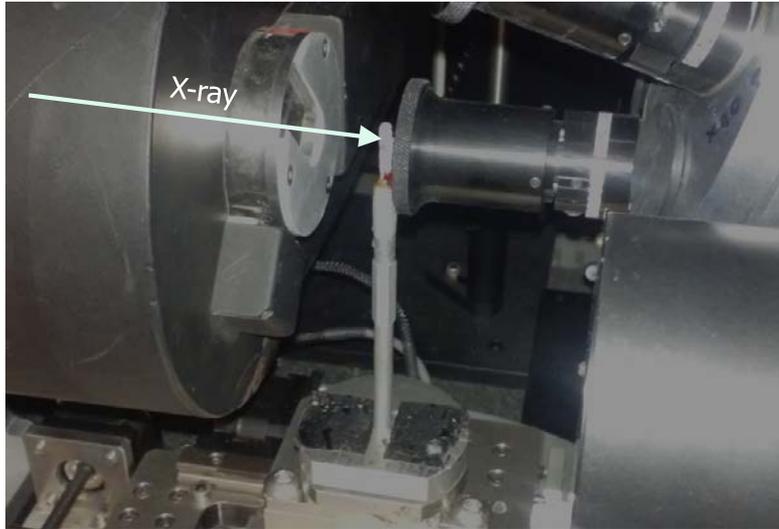
Complex bends



90° bends

Additional CSM capabilities

- Zeiss X-ray CT (computed tomography)



- CT scan to see the skeleton of the composite!

- 0 / 90 / 0 glass fiber

The Institute for Advanced Composites Manufacturing Innovation

Acknowledgements

- Colorado Office of Economic Development Industry and Trade (CO OEDIT) with special thanks to Katie Woslager.
- The IACMI team in Tennessee.
- You for your attention!

- **Commissioned two new facilities**
 - VARTM lab at Colorado School of Mines (CSM)
 - Blade component manufacture at NREL
- **Property database creation**
 - Collected rheological data for liquid precursor and curing resin
 - Established testing protocols and plan for comparison to thermosets
- **Developed chemical kinetics / heat transfer model**
 - Initiated tech transfer to Convergent for *Raven* process simulator.
- **Developed NDE plan (Vanderbuilt / ORNL group)**
- **Demonstrated that PCMs can shorten cycle times**
- **Filed 1 patent, submitted 1 paper + 1 CAMX abstract, 2 more patents in preparation.**



Materials and Process Development for Direct Digital Manufacturing of Vehicles

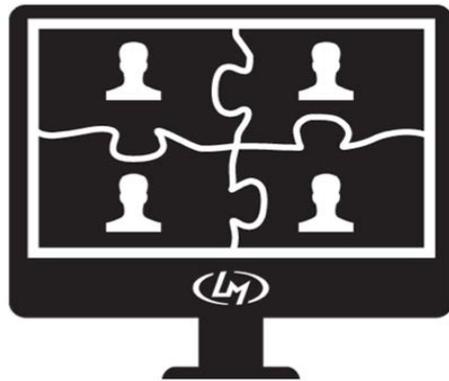
Charles Hill, Greg Haye, Robert Bedsole, and Kyle Rowe
Local Motors

Institute for **ADVANCED**
Composites Manufacturing
INNOVATION

July 27, 2016

Who is Local Motors?

Local Motors is a technology company that designs, builds, and sells vehicles.



Ideate, design and engineer products collaboratively.

+



Prototype, test and make products locally.

Through Co-creation and Micro-manufacturing

Co-creation Community Development

Community members earn royalties from the products that we commercialize.



World's 1st 3D-Printed Car

STRATI



What is Direct Digital Manufacturing?

Direct Digital Manufacturing (DDM) is the ability to manufacture parts directly from a computer-aided design (CAD) file.

- “**Click, Print, Drive**” - Combination of DDM Methods:
 - Additive Manufacturing Processes
 - CNC Machining Subtractive Processes
 - Assembly Operations
 - Factory Automation
- Why 3D Printing?
 - Allows **Rapid Design and Development Cycles**
 - Enables Customer Configuration and On-Demand Build Capability
 - **Reduces Embodied Energy** From Vehicle Manufacturing
 - Recyclability of Thermoplastic Parts: Grind, Re-pelletize, Re-print

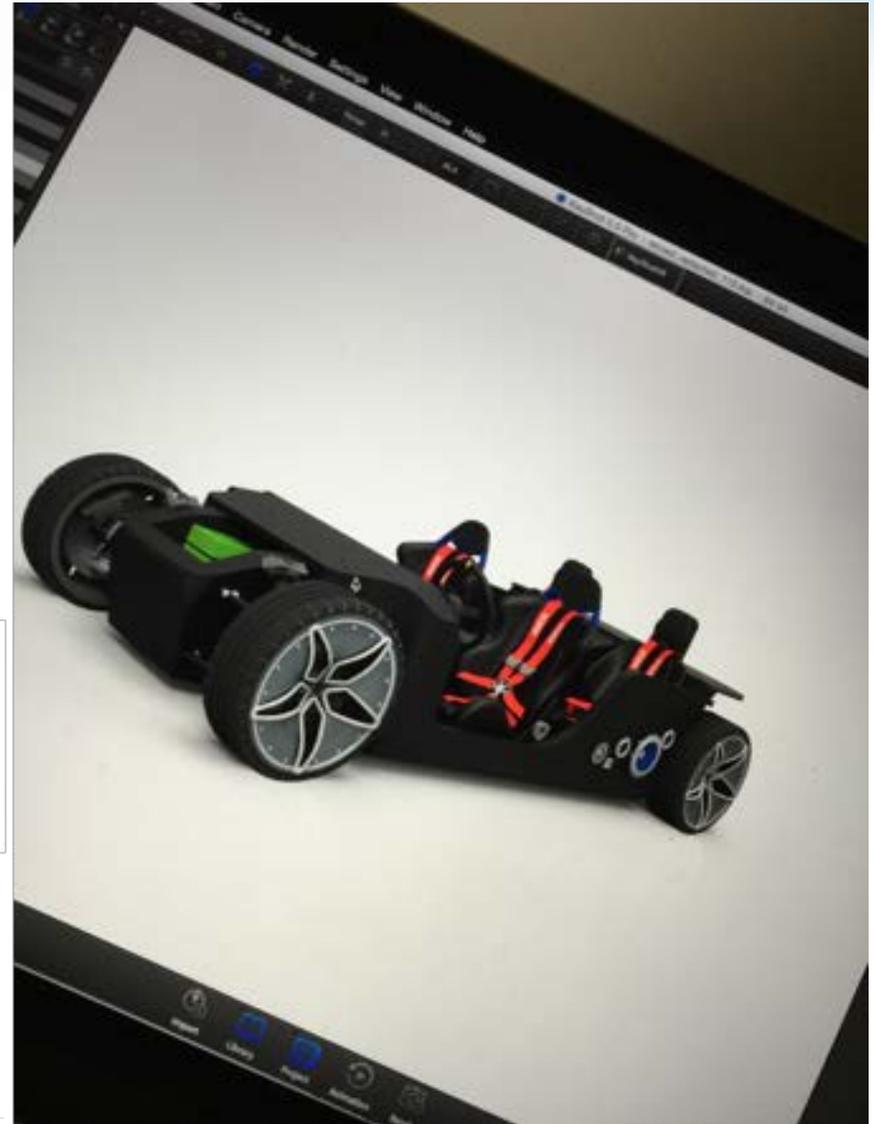


Highway Car Design Challenge

Project: Redacted



Swim and Sport



Concept Vehicle in Less than 2 Months

LM3D Series v1

LM3D



Olli Autonomous Transportation System



Low Speed Electric Vehicle: Olli

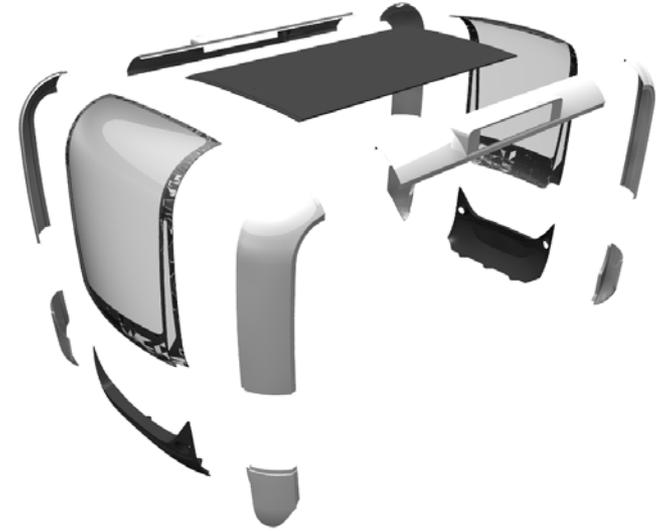
Advanced Materials and Manufacturing Processes

- BAAM Printed Molds:
 - Used for Vacuum Thermoforming of ABS Sheet for Interior Panels:
 - Over 15 Molds Produced in 5 Days for Pilot Program Vehicles.
 - Evaluating These Parts for Composite Application.
- BAAM Printed Parts:
 - 11 Individual Parts Produced Directly by Large Scale 3d Printing.
 - Fenders and Wheel Wells, Front and Rear Panels, Interior Kick Panels.
- Conventional Composites:
 - Carbon Fiber/Epoxy Roof and Corners.
 - Formed with Traditional Tooling Board.
 - Will use BAAM Printed Tools in the Future.

Olli Manufacturing Details



Direct Additive Parts



Composite Panels



Thermoformed

Cincinnati BAAM Large Scale Additive

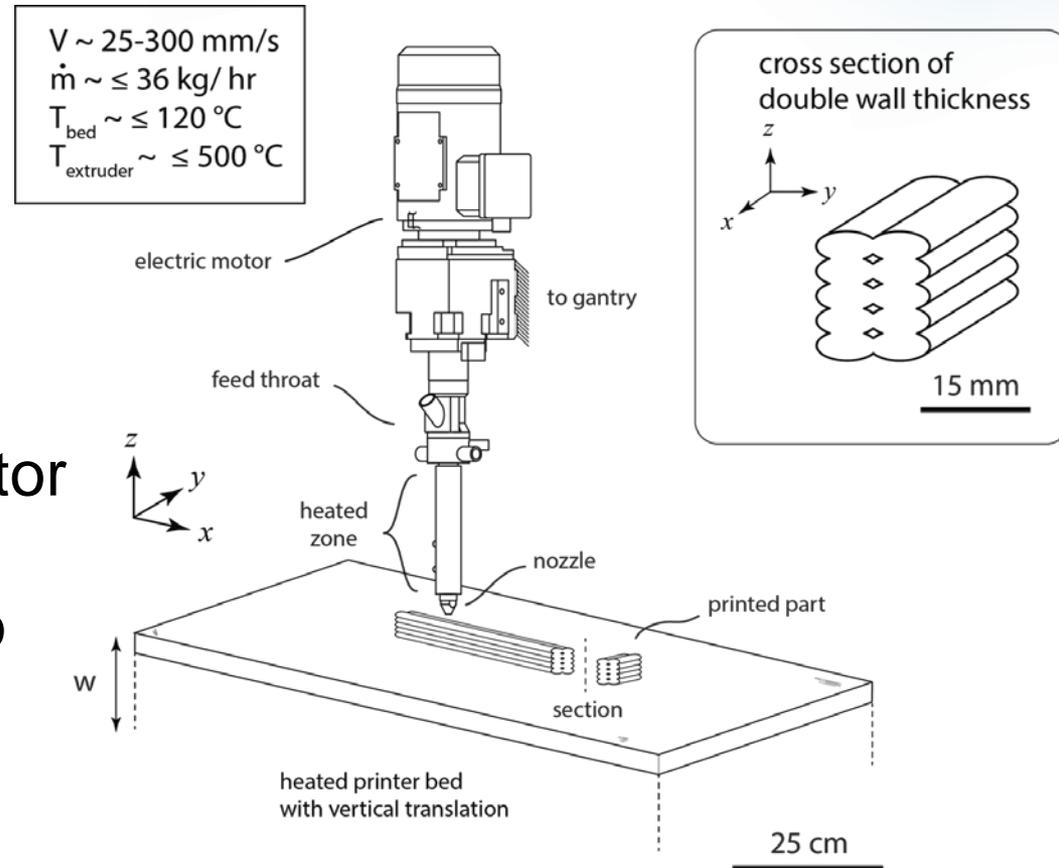
Operating Three Machines Today



Phoenix, Knoxville, National Harbor

Extrusion Deposition Process

- Pellet Feed System
- Single Screw Extruder
 - 5 Zone Temperature Control
 - 24:1 L/D
- X, Y, Z Gantry Manipulator
- Dynamic Speed Control
 - Match Pump RPM to Linear Velocity



Materials and Process Overview

The Rapid Design-to-Manufacture of Production Automotive Vehicles Will Require the Development of:

- A Material Property Database for Current Material
 - 20% Chopped Carbon Fiber in ABS Resin (CF/ABS)
- New Materials Tailored for Printing
 - New Combinations of Polymers, Fillers, and Nanofillers
- An Understanding of the Effects of Print Parameters on Mechanical Properties
 - Extrusion Temperature, Environment Temperature, Bead Aspect Ratio, % Bead Overlap, Print Speed.
- New Manufacturing Techniques for Reinforcement of Printed Structures
 - Carbon Fiber Overwrap, Foam-Filling, Infill Patterns, Metal Inserts.

Materials Characterization

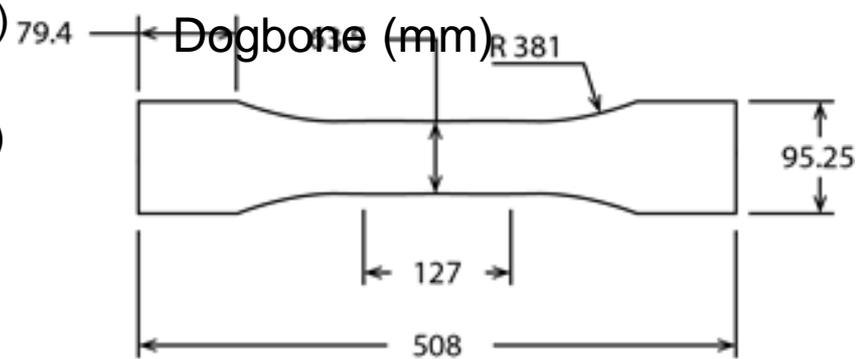
Completed work includes:

- Tension (508 x 95 x 13 mm outer dimensions)
- Flexure (305 x 51 x 13 mm)
- Fatigue (508 x 95 x 13 mm outer dimensions)

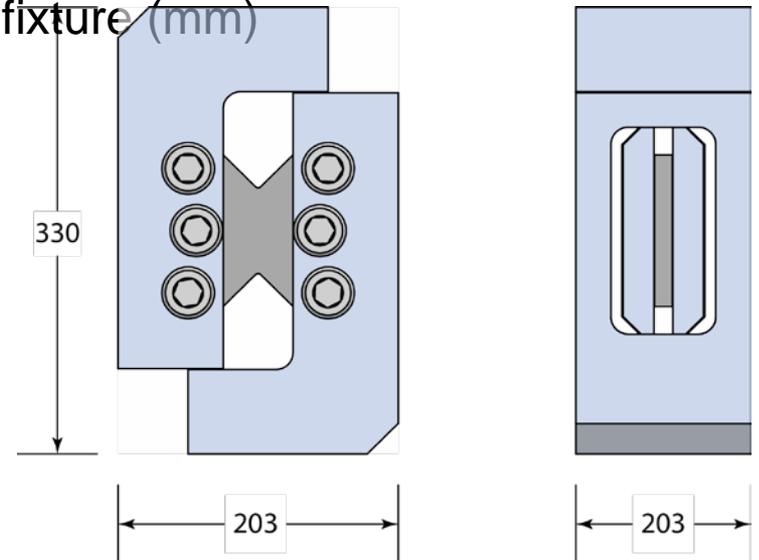
Planned work includes:

- Shear
- Fracture
- Charpy Impact
- Static Compression
- Dynamic Compression/Crush
- Moisture and Temperature
- Rheology
- DSC
- TGA
- TMA
- Microscopy

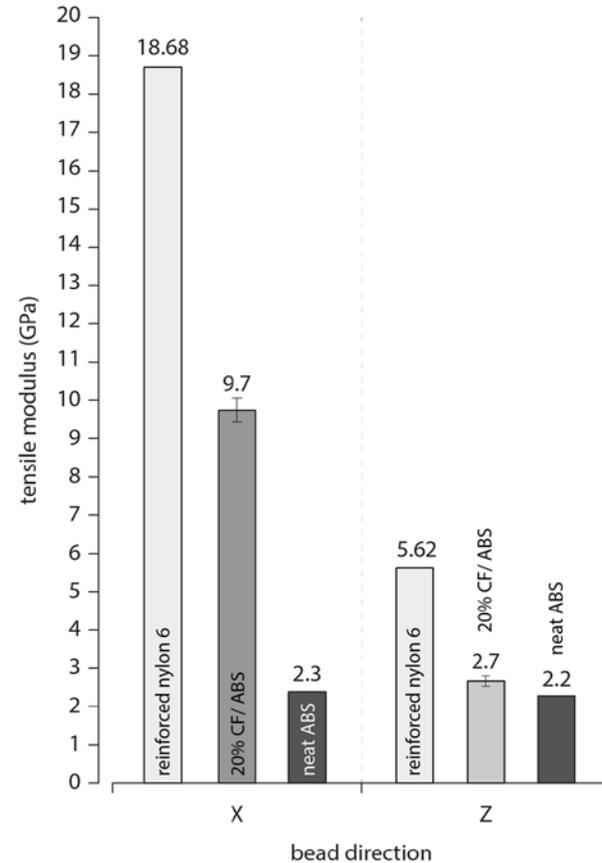
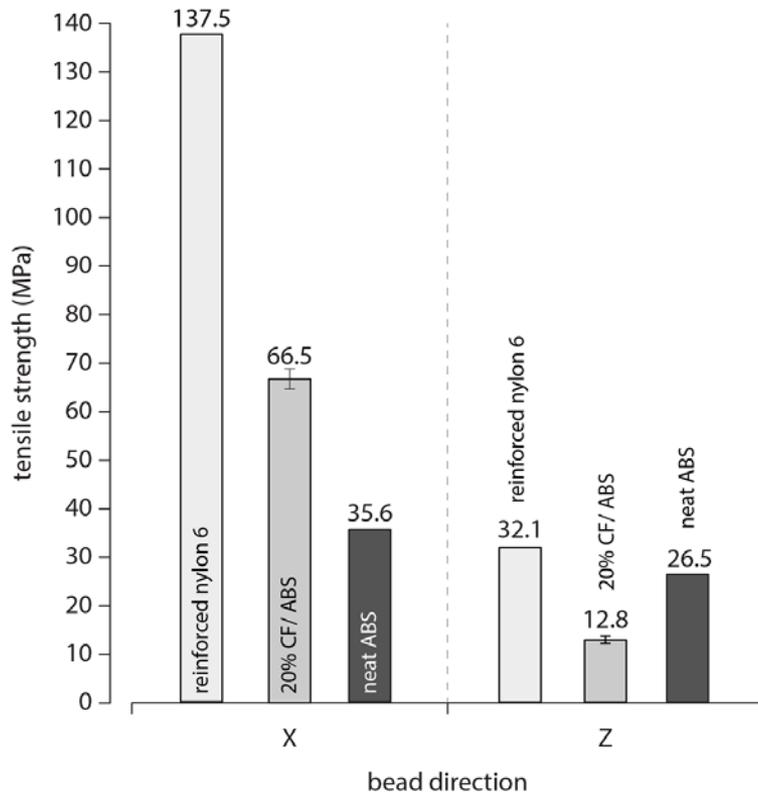
Modified ASTM-D-638



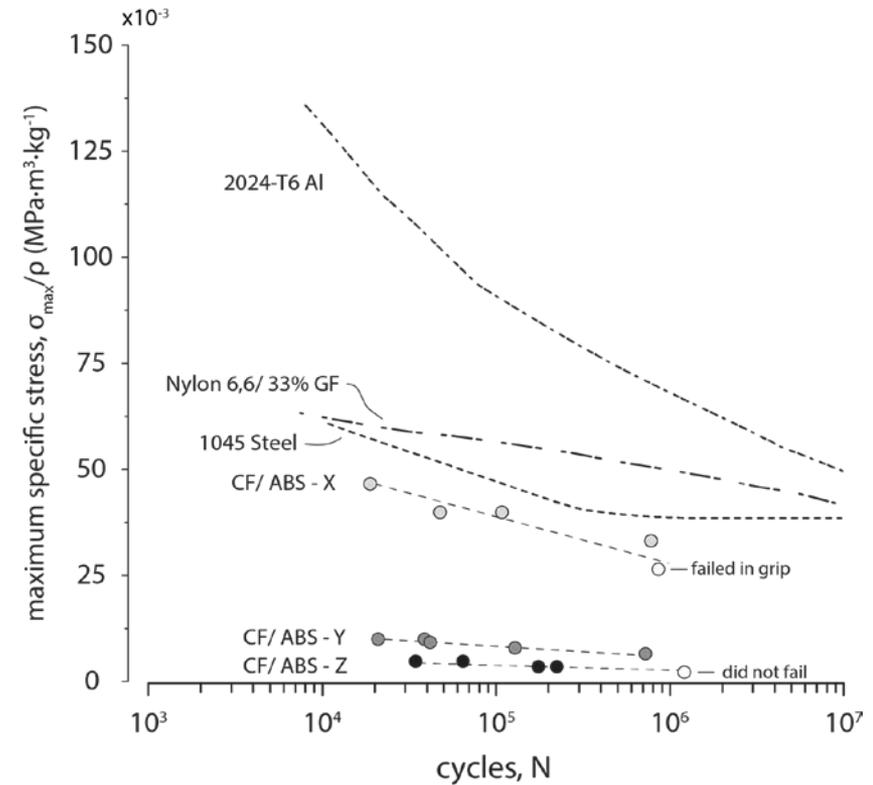
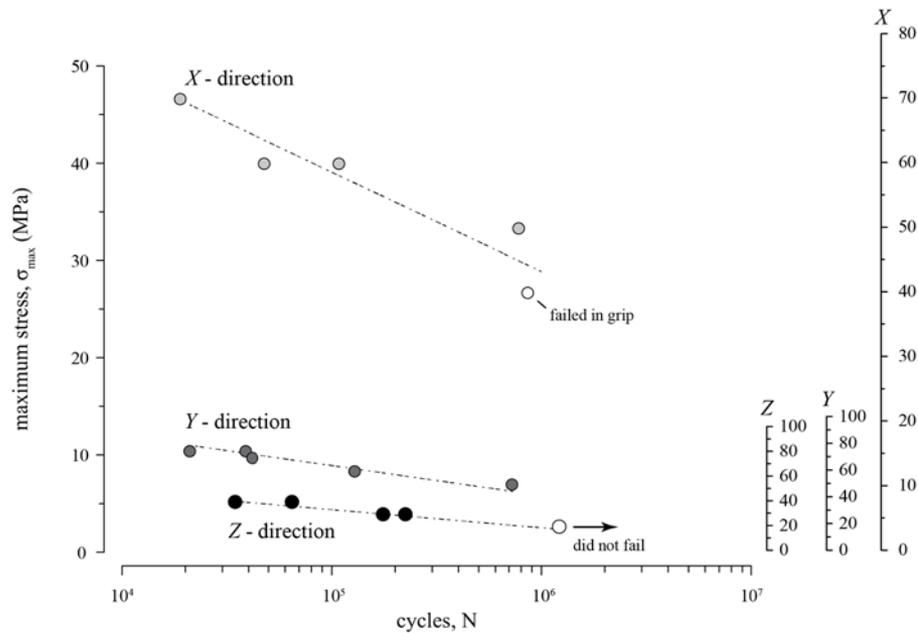
2X ASTM-D-7078 V-notch rail shear fixture (mm)



Tensile Results of Printed Materials

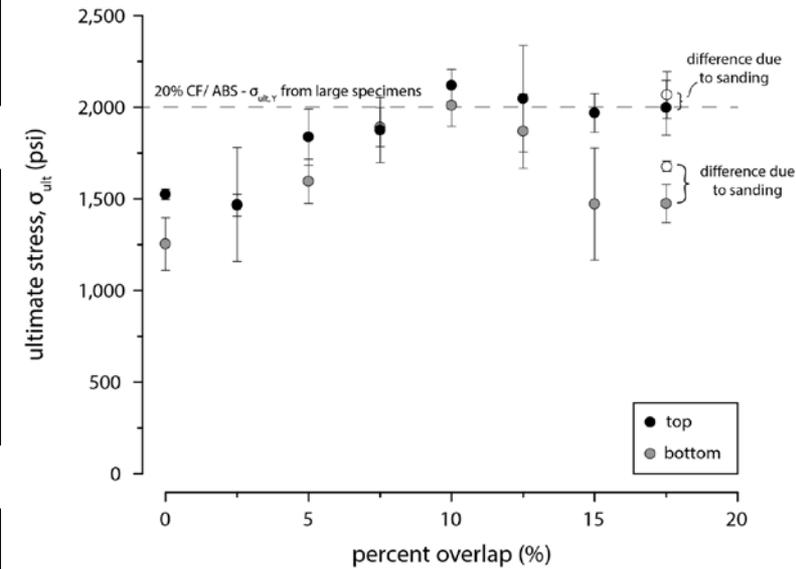
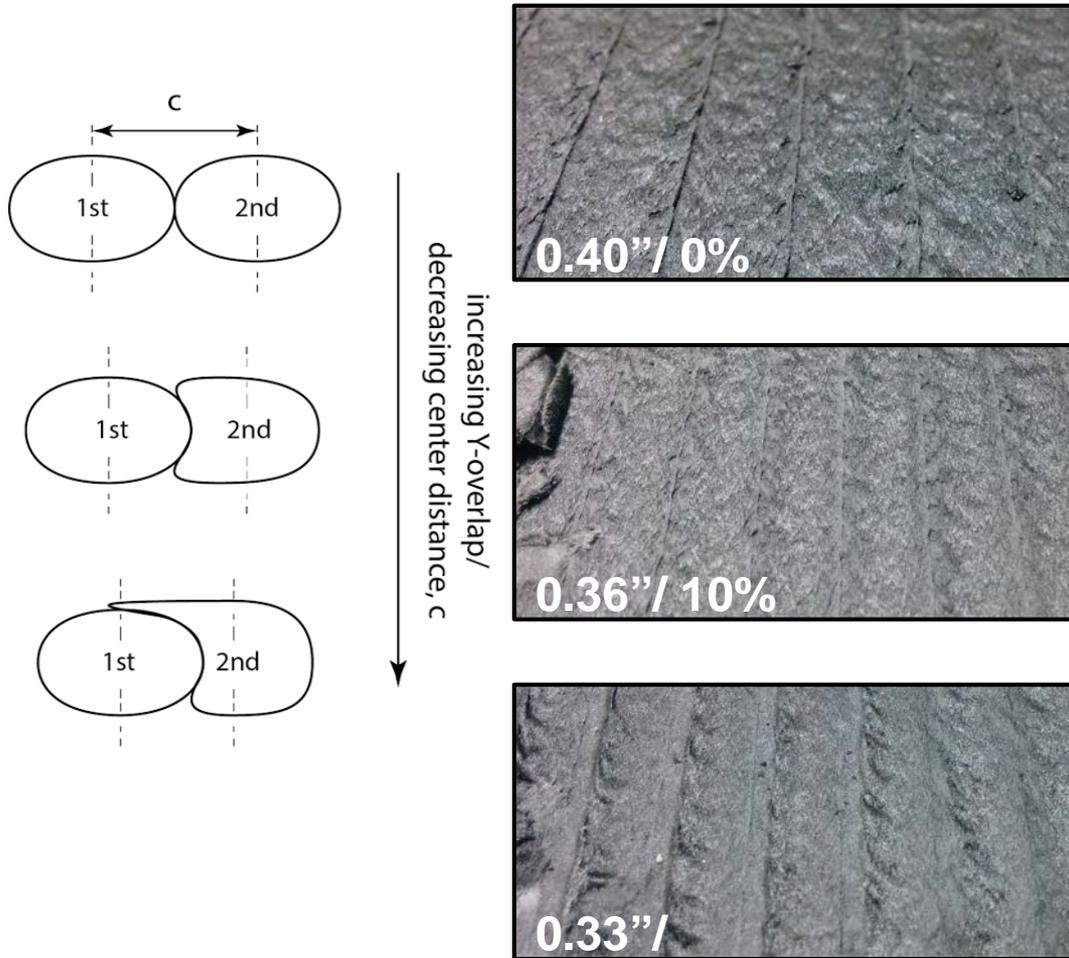


Fatigue Results

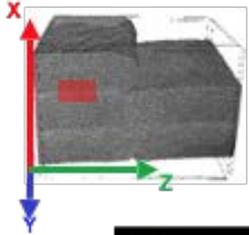


Process Parameter Studies

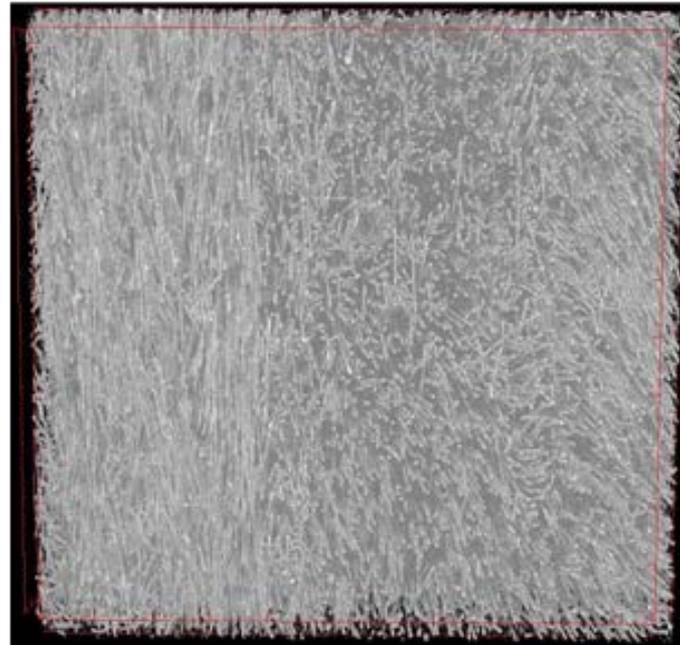
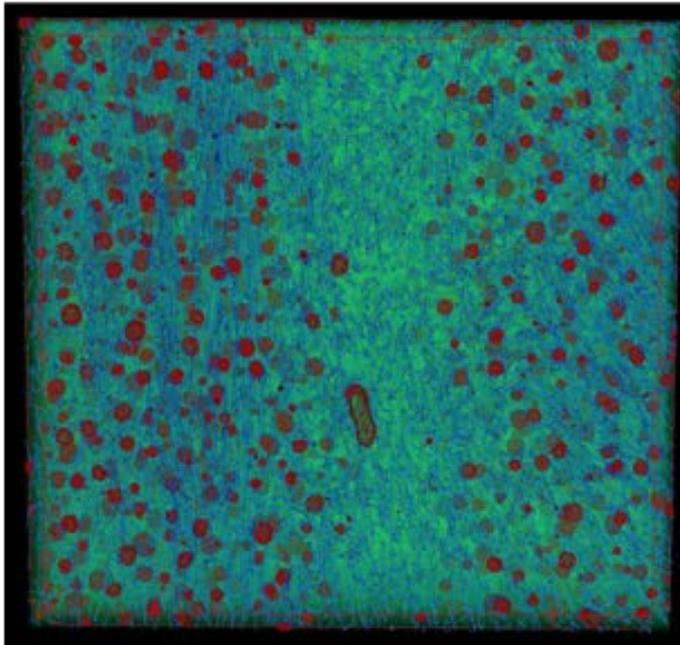
Effect of Bead Overlap



Computed Tomography of Printed Bead



Ricardo Rodriguez* and Jenny Sietins
Materials and Manufacturing Sciences Division
*ricardo.x.rodriguez4.ctr@mail.mil 410-306-0854



Blue = Fibers
Red = Pores
Green = Matrix

 = 100 μm

New Materials Development

Resins

- Nylons
- Polyesters
- Polyphenylene Ether
- Polyphenylene Sulfide
- PC Blends



Reinforcements

- Carbon Fiber
- Glass Fiber



Nanofillers

- Graphene
- Nanocellulose
- Mineral



Reinforcement of DDM Structures

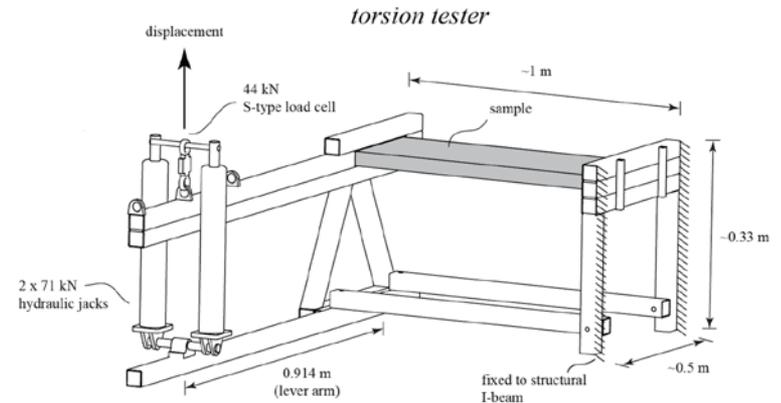
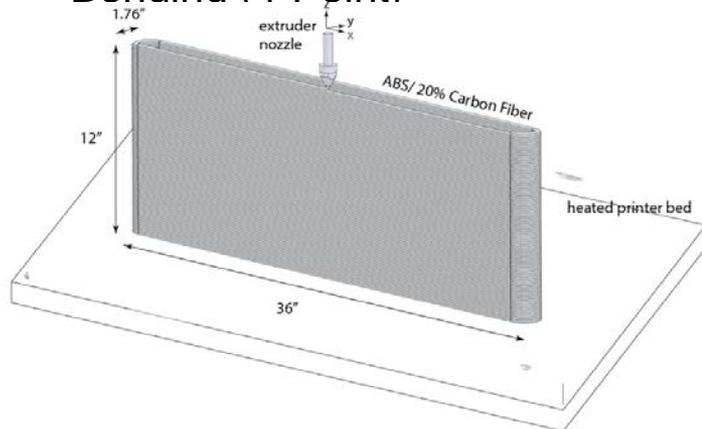
Communicate to Design Team a Variety of Techniques and Their Effectiveness

Reinforcement Methods:

- Structural Foam Fillers
- Composite and Metallic Inserts
- Carbon Fiber Inlays and Overwraps
- Printed Internal Support Structures

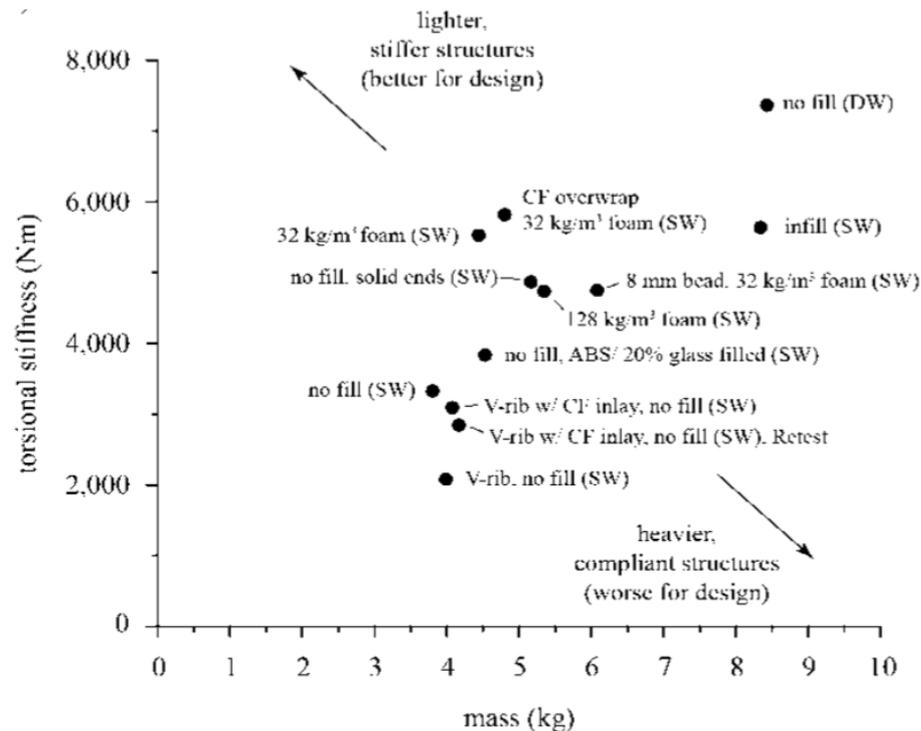
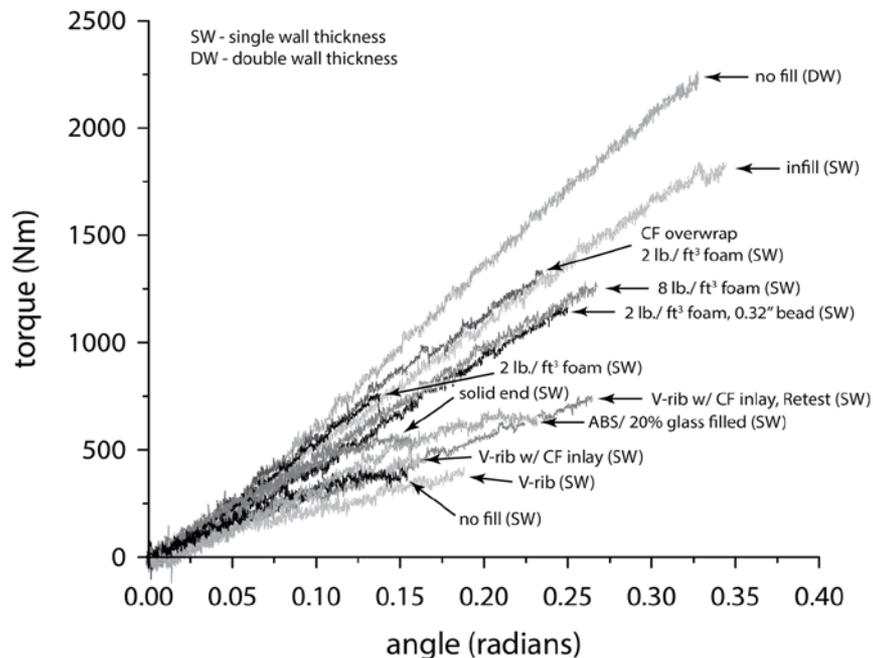
Testing and Evaluation

- Torsion
- In-Plane Shear (Rail Shear)
- Bendina (4-Point)



Reinforced Structures: Torsion Results

Multi-material Structural Sub-Elements



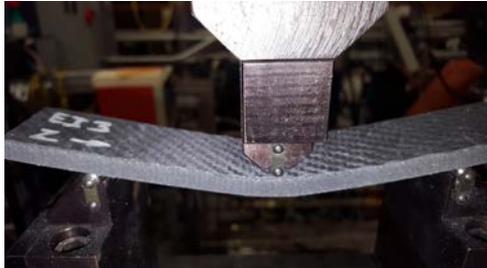
Reinforcement of DDM Structures



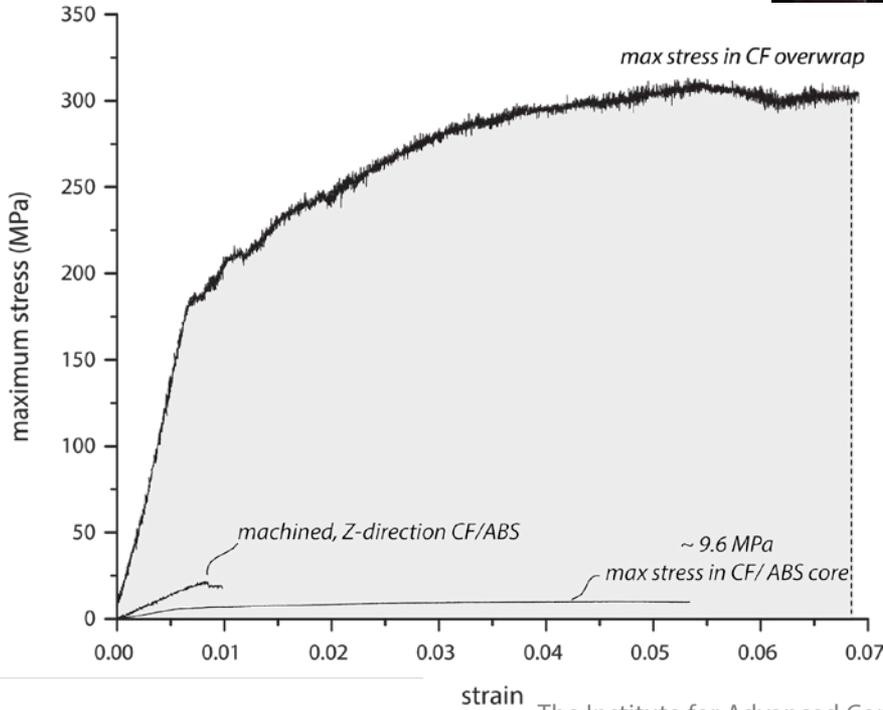
Z-Direction Specimen



2 ply, 2x2 twill fabric, 3K, AS4 Carbon Fiber



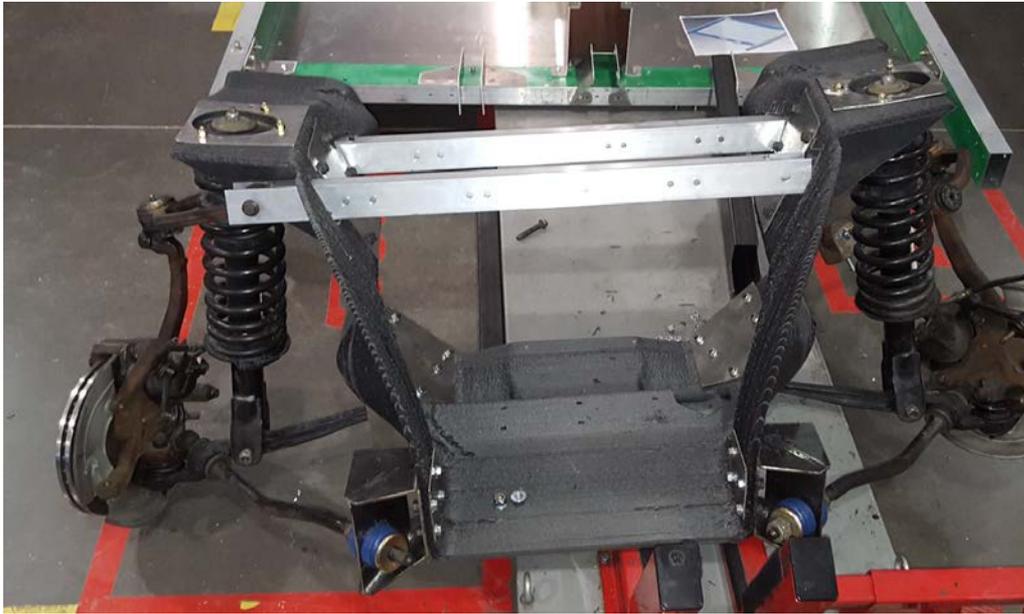
Arkema Elium Reactive Infusion of PMMA



3-point Flexure:
Comparison of Z-axis printed beam with printed and overwrapped beam

Composite Overwrap Full Scale Demo

Highway Car Construction Mule Front Section



Printed part mocked-up with suspension and chassis mounts



Layup of dry fabric on printed part

Composite Overwrap Full Scale Demo



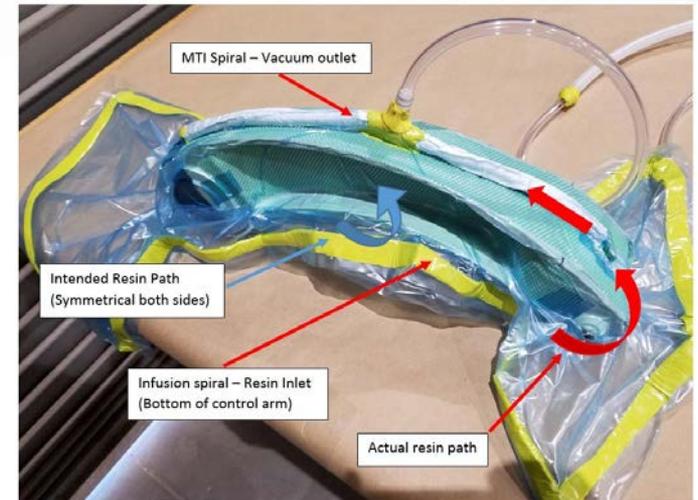
- Envelope bagging for resin infusion process
 - Reusable bags for production.
 - Metal inserts may be pre-placed.
 - May produce complex shapes not possible with conventional tooling.



- Partially assembled beta vehicle “Construction Mule” in three sections:
 - Composite overwrapped front.
 - Bonded aluminum tubing center.
 - All printed with aluminum sheet rear.

Overwrap Infusion with Metal Inserts

- Control Arm with Metal Inserts.
- 3d Printed Core.
- Machined for Location of Inserts.
- Braided Tube Carbon Overwrap.
- Delrin Plugs to Mask Holes.



Inserts securely bonded in place

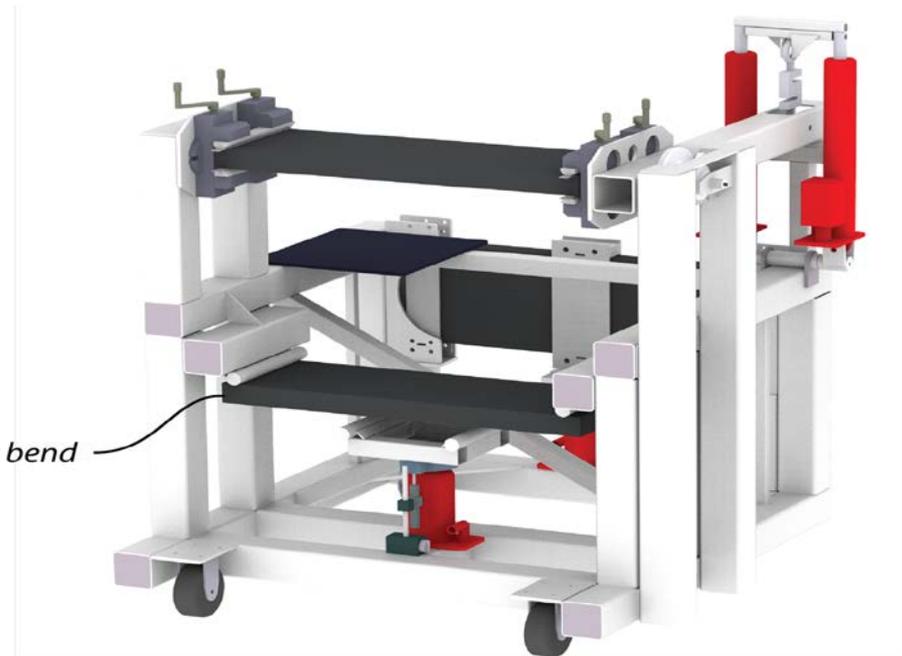
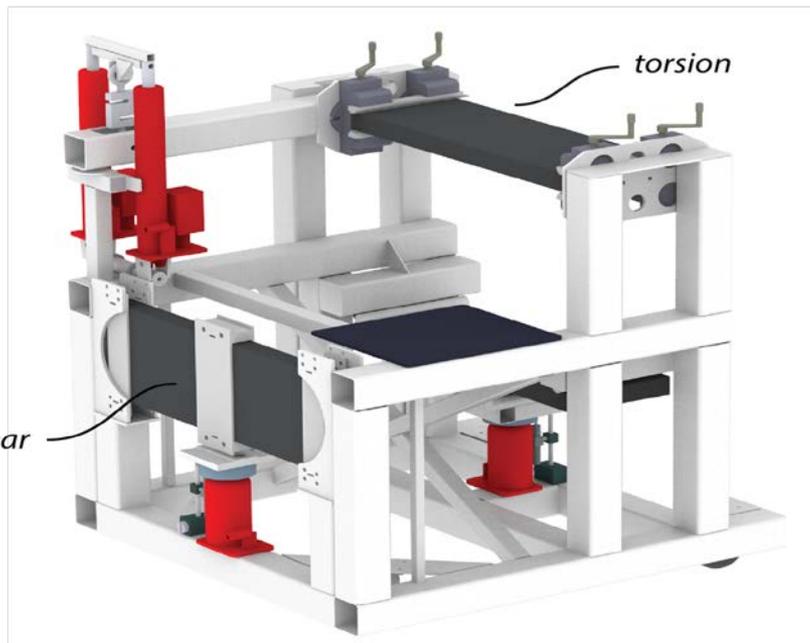
IACMI Phase 1 Materials Development

- Fundamental Understanding of Printability
- Explore new thermoplastics and reinforcements
 - Nylons, PPO, Polymer Blends
 - Rheology (viscosity vs temperature and shear rate)
 - DSC (heat of fusion and phase transitions)
 - TMA (CTE and phase transitions)
 - Curl Bar (Dimensional Stability)
 - Mechanical Properties
 - Impact Performance



IACMI Phase 1 Structural Testing

- 1' x 3' x 2.5" Multi-material Structural Subelements
- 37 Different Design Configurations
- Full Field Displacement Measurement by DIC



IACMI Phase I Schedule

#	Traits	Title	Given Earliest Start	Given Work	Resources	Predecessors	Q2 / 2016		Q3 / 2016			Q4 / 2016			Q	
							5	6	7	8	9	10	11	12		
0	📁🕒	IACMI Phase I Local Motors	7/27/16													1
1		Start														
2	🕒	Materials Development				1										
3		Acquire Samples		1.6 weeks ?												
4		BAAM Printability Testing		4.7m?												
5	🕒	Rheology, TMA, DSC	8/21/16	2.46 months												
6	🕒	Data Analysis	10/20/16	1.61 months												
7	🕒	Downselect Three Materials	12/11/16	2 weeks												
8		Structural Testing														
9		Acquire Materials and Designs		1 month												
10	🕒	Manufacture Sub-Elements	7/30/16	2 months												
11	🕒	Test Sub-elements Bending	9/19/16	3 weeks												
12	🕒	Test Sub-elements Torsion	10/3/16	3 weeks												
13	🕒	Test Sub-Elements Shear	10/24/16	3 weeks												
14	🕒	Data Analysis	11/7/16	3 weeks												
15		Final Report				2										

IACMI Phase II Planning

Objectives:

1. Further Develop Materials and Equipment for Large Scale Additive Process.
2. Develop and Verify Simulations of BAAM Process and Mechanical Performance.
3. Design, Simulate, Build, and Test Vehicle Structure Using Results of Objective 2.

Discussions with Potential Partners to Identify Tasks:

- Lockheed Martin (OEM)
- Cincinnati Inc. (equipment modifications)
- Purdue University/Dassault (analysis and simulation)
- BASF, Sabc, Techmer ES, PPG (materials suppliers)
- Michigan State University (surface treatment/reversible bonding)
- Vanderbilt University (NDE)

Thank You

Questions?



LOCAL MOTORS





Reclaimed Carbon Fiber Reinforced Automotive Part using 3-DEP Preforms and Preform Tooling using Reclaimed Carbon Fiber and MDF's Additive Manufacturing Process

Institute for **ADVANCED**
Composites Manufacturing
INNOVATION

Jim Stike, Materials
Innovation Technologies

Materials Innovation Technologies Carbon Conversions, Inc.

- Advanced materials company that reclaims and repurposes carbon fiber composites.
- Vehicles, Consumer Electronics, Medical Equipment, Sporting Goods.
- Chopped fiber (compounding), nonwoven roll goods (prepreg), net shaped preforms.
- Benefits: 100% of carbon fiber composite scrap can be recycled, lower cost preform tooling, super fast prototype development, lower cost preforms.

Reclaimed Carbon Fiber Reinforced Automotive Part using 3-DEP Preforms and Preform Tooling using Reclaimed Carbon Fiber and MDF's Additive Manufacturing Process

- **Challenge:** Cost and manufacture time of preform tooling is a significant challenge to implementation of advanced processes such as 3-DEP, which has been demonstrated as a viable method for making preforms from discontinuous recycled carbon fiber.
- **Approach:** Use of Big Area Additive Manufacturing (BAAM) to create tooling for 3-DEP will enable deployment of discontinuous RCF preforms made from 3-DEP.
- **Impact:** *Decreased design-manufacture cycle time for CFRP components and increased use of recycled carbon fiber.*
- **Materials Innovation Technologies, ORNL/UT**
- Materials and Process
- TC Phase 1
- TRL/MRL Impact: from 7 to 8



3-DEP™ Is Ideally Suited to Processing Recycled or Reclaimed Fibers

F-18 fiber from Boeing, chopped, 3-DEP™ preform, and molded



Project Description and Status Update

- Phase I results will show low cost/fast tooling to produce a lower cost/fast cycle time preform.
- Phase II collaborators include Dow, Faurecia, Local Motors
- Phase II will pick a large, production vehicle component. We will optimize weight and cost using printed tooling made with reclaimed fibers and reclaimed carbon fiber preforms.
- We welcome any and all collaborators interested in using reclaimed carbon fiber.