U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

ADVANCED MANUFACTURING OFFICE

Fiber Reinforced Polymer Composite Manufacturing Workshop:

Summary Report

January 13, 2014
Arlington, VA

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

THE DEPARTMENT OF ENERGY (DOE)'S ADVANCED MANUFACTURING OFFICE PROVIDED FUNDING FOR THIS MEETING AND SUMMARY REPORT.

The DOE Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office partners with private and public stakeholders to support development and deployment of innovative technologies that can improve U.S. competitiveness, save energy, and ensure global leadership in advanced manufacturing and clean energy technologies.

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Introduction

Lightweight, high-strength and stiffness composite materials have been identified as a key cross-cutting technology for reinventing energy efficient transportation, enabling efficient power generation, providing new mechanisms for storing and transporting reduced carbon fuels, and increasing renewable power production.[1] Fiber reinforced polymer composites can be used in vehicles, industrial equipment, wind turbines, compressed gas storage, buildings and infrastructure, and many other applications.

Improvements and innovation in manufacturing and assembly techniques for fiber reinforced polymer composite materials and structures are needed to meet cost and performance targets to enable wider adoption across multiple industries.[2] Addressing the technical challenges may enable U.S. manufacturers to capture a larger market share of the higher value add of composites in the supply chain and could support domestic manufacturing competitiveness.

The DOE Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office (AMO) partners with private and public stakeholders to support development and deployment of innovative technologies that can improve U.S. competitiveness, save energy, and ensure global leadership in advanced manufacturing and clean energy technologies. AMO supports cost-shared research, development, and demonstration of innovative, next-generation manufacturing processes and production technologies that will improve energy efficiency as well as reduce emissions, industrial waste, and the life-cycle energy consumption of manufactured products.

This document summarizes the Fiber Reinforced Polymer Composite Manufacturing workshop held at the Hilton Crystal City in Arlington, VA on January 13, 2014. The workshop fostered an exchange of information on technical issues and manufacturing challenges related to achieving low-cost fiber reinforced polymer composites and impacting U.S. manufacturing competitiveness and energy efficiency. The workshop included presentations by government personnel as well as facilitated breakout sessions to gather input from participants. Over 145 attendees participated, representing automotive, wind turbine, fuel cell, and other markets, as well as the national laboratory, academic, and government perspectives. The names of participants are listed in Appendix 1. The meeting agenda and information sent to participants in advance of the meeting are in Appendix 2. The presentations from the workshop are available on the Advanced Manufacturing Office (AMO) website. This document summarizes the information exchanged and gathered at the workshop.

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[1] The Minerals, Metals and Materials Society (2012). *Materials: Foundation for the Clean Energy Age.* Retrieved from http://energy.tms.org/docs/pdfs/Materials_Foundation_for_Clean_Energy_Age_Press_Final.pdf

[2] The Minerals, Metals and Materials Society (2011). *Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization, Innovation Impact Report*. Retrieved from http://energy.tms.org/docs/pdfs/Phase_III_Report.pdf

Dr. Mark Johnson, Director of the Advanced Manufacturing Office, started the day with welcoming remarks, reviewed the agenda, and introduced Dr. David Danielson, Assistant Secretary for Energy Efficiency and Renewable Energy (EERE). Dr. Danielson set the stage for the day by describing EERE's mission to create U.S. leadership in the transition to a global clean energy economy. In addition to the applicability and potential for lightweight composite materials in a wide range of applications, the Assistant Secretary noted that EERE was launching a cross-cutting initiative on carbon fiber composites to better coordinate and strategically align EERE programs. Dr. Danielson laid out an initial framework for the initiative that included three focus areas: diversification of feedstocks for carbon fiber, including bio-based materials or natural gas; lower energy conversion of white fiber to carbon fiber; and composite manufacturing.

Dr. Johnson then provided detailed information on the Advanced Manufacturing Office's mission, programs, and reviewed the summary results from two Requests for Information (RFIs) that were released by AMO in August 2013 and in December 2013. Summaries of the two RFIs can be found on the AMO website.

After Dr. Johnson's overview, a panel of experts from across DOE discussed the use of composites for clean energy and industrial applications, including a high level summary of existing R&D programs within their respective offices. The panel participants included Jim Ahlgrimm (Wind and Water Technology Office), Jerry Gibbs (Vehicles Technology Office), Scott McWhorter (on behalf of Fuel Cells Technology Office), and Dane Boysen (ARPA-E). AMO's Mark Shuart was the panel moderator. Key comments from the panel included the following:

- **Wind**: The trend is for larger turbines that can produce energy at a lower cost with long-term reliability. This is particularly important for offshore systems that can be three times the size of land-based turbines. All reasonable technology options to reduce cost will be considered. Off shore reliability is important, so somewhat higher costs for higher performance materials can be tolerated.
- **Hydrogen Storage**: The carbon fiber composite overwrap is estimated to make up over 60% of the cost of hydrogen storage for vehicles at a production volume of 500,000 systems per year. Cost is a key barrier to wider adoption of hydrogen storage systems. The DOE Fuel Cells Office has supported different strategies to reduce the cost and develop alternate materials and novel designs.
- **Natural Gas Storage**: For use as a transportation fuel, it is necessary to compress natural gas to achieve practical energy densities. A barrier to natural gas use in light-duty vehicles is the high volumetric density. The physical size and poor "form-factor" of typical (cylindrical) storage tanks can significantly limit trunk space in passenger vehicles. Lightweight, low-cost, conformable materials are needed.
- **Vehicles**: Lightweighting can reduce petroleum consumption through improved fuel efficiency. These improvements will impact all forms of transportation, especially ground transportation where a 10% weight reduction translates to approximately 7%-

8% better fuel economy. These improvements can be especially impactful for heavy duty vehicles. For example, a typical (class 8) heavy duty truck weighs over 33,000 lbs and will travel over 100,000 miles per year. They can be early adopters of lightweighting technology because of the direct economic impact.

During the question and answer period, panelists commented that for many of these applications, carbon fiber composites are the best available technology. However, other fibers reinforced materials and integrated approaches that can meet the performance and cost targets could be acceptable. Material acceptability of the composites would be application specific.

Frank Gayle, Deputy Director of the Advanced Manufacturing National Program Office (AMNPO), provided an overview of two key interagency advanced manufacturing activities: the National Network for Manufacturing Innovation (NNMI) and the Advanced Manufacturing Partnership 2.0. Next, three inter-agency partners from DARPA, NASA, and NSF discussed the advanced manufacturing of composites based on their respective Agencies and mission needs. The following is a summary of their remarks:

Mick Maher from DARPA discussed the ongoing Open Manufacturing program which includes building confidence in the materials through a technology insertion program, increasing bonded composite confidence, developing informatics/probabilistic processes to improve scale-up of processes, and a manufacturing demonstration facility for composites. Mr. Maher also shared a insights from a workshop held by DARPA and the National Science Foundation (NSF) in August 2013: composites are a commodity sold by industry and material type. The issues are broader than technical and economic. Meeting the application and marketplace requirements is more important than the economics. The technology requirements for composites vary across the entire application landscape. A unified approach to advancing composites in different applications is not evident.

John Vickers from NASA discussed composites work across the Agency (~120 activities), with about 30 activities focused on carbon fiber reinforced applications. Mr. Vickers said affordability is the biggest challenge (getting out of the autoclave), along with the predictability of performance-modeling and simulation. He provided several examples including: a composite cryotank project that is 5.5 meters in diameter, extremely low weight (<30% than state-of-the-art, <25% of cost), and required many individual tests and prototypes to develop; the James Webb Space Telescope Primary Mirror Backplane Structure which requires extreme thermo-stability and is carbon fiber reinforced; and the upper stage of the new NASA Space Launch System is being modelled as a composite instead of just aluminum.

Steve McKnight provided an overview of NSF’s activities in composite materials research and related education programs. He focused on NSF's role as a supporter of fundamental research within their "core" research programs, as well as NSF's innovation programs including the Engineering Research Centers, University/Industry Cooperative Research Program (I/UCRC), and iCorps programs. Dr. McKnight also mentioned NSF's support for STEM education including the Graduate Research Fellowship Program and the Advance Technological Education (ATE) program. He challenged the research community with a question, “can we identify promising technologies earlier using more robust and higher fidelity computational modeling?” He urged the community to consider the integration of overarching design approaches and the materials selection process when designing components for performance and value enhancements in specific markets.

Afterwards, Dr. Johnson provided instructions for the breakout sessions and closed the morning session. After lunch, the participants convened with their breakout groups. The breakout groups covered three focus areas:

1. **Manufacturing Process Technologies** - Blue Teams A and B (e.g., lay-up techniques, out of the autoclave, novel cure techniques, resin infusion, pultrusion, sheet molding compound, tooling, machining)
2. **Enabling Technologies and Approaches** - Red Team (e.g., design methods and databases, analytical tools, nondestructive evaluation, damage tolerance, joints, repair, other)
3. **Recycled and Emerging Materials** - Green Team (e.g., recycling carbon fiber, renewable precursor materials, advanced glasses, nanomaterials)

As a discussion starter in each breakout session, participants presented one slide summarizing a key technology and the limitations. These slides, without attribution to the author, are provided on the AMO website. (Several Technology Readiness Level (TRL) lists are used across the Federal government. For purposes related to AMO, please see “The National Network for Manufacturing Innovation: A Preliminary Design,” National Science and Technology Council, January 2013, p.8.)

Each group considered the following discussion questions:

- Identify a **specific key technology** that has the potential to help achieve these objectives, the **target application areas,** or whether the technology is cross-cutting.
- What is the **state-of-the-art** for this technology? What is the Notional Technology Readiness Level/Manufacturing Readiness Level (TRL/MRL) - basic research, applied, pilot scale, commercial?
- What are the **current limitations/challenges** to this technology, in particular for use in clean energy and industrial applications? What prevents industry from doing this on its own?

Participants answered and discussed these questions considering their group’s focus area and the potential objectives for composites manufacturing as outlined in the summary of the input from the December 2013 RFI (the second RFI). Specifically, have an impact on clean energy and industrial applications: 1) reduce cost, 2) increase production rate, 3) lower energy and 4) increase recyclability of fiber reinforced polymer composites. At the closing session of the workshop, a summary of the comments from participants in each breakout session discussion was presented. The input gathered from participants during the four breakout sessions is provided in the next section of this document.

Summaries of the Breakout Session Discussions

Manufacturing Process Technologies – Blue Team A

Table 1 presents Blue Team A participants' comments regarding key manufacturing process technologies, application areas for those technologies, the state-of-the-art, and the limitations and challenges facing the technology today.

Table 1. Summary of Blue Team A participants' comments related to manufacturing process technologies.

Key Technologies
1. Alternative resin chemistries (hybrid resin systems, blends) *Application Areas:* Cross-cutting *State-of-the-art:* TRL 9 *Limitations/Challenges:* ○ Demonstrate inadequate interlaminate shear in final product form ○ May have poor fire, smoke, and toxicity (FST) performance ○ May not have proper viscosity for processing ○ Typically are not recyclable
2. High pressure resin transfer molding (RTM) and rapid cure thermosets *Application Areas:* Automotive *State-of-the-art:* TRL 8-9 *Limitations/Challenges:* ○ The time required to fill the part is the rate limiting process step ○ Equipment and tooling are expensive for resin transfer molding systems ○ There is a trade-off between RTM processing speed and fiber volume fraction
3. Automated placement of prepreg, tow and tape *Application Areas:* Cross-cutting *State-of-the-art:* TRL 9 for aerospace; not ready for automotive *Limitations/Challenges:* ○ Equipment and material are typically expensive ○ Programming the equipment automation is challenging ○ Lack of technical skills in the workforce hinders technology uptake ○ Process is limited by rate of material placement (lbs/hour) ○ Difficult to make complex shapes with this process limited to certain geometries
4. Rapid preforming *Application Areas:* Cross-cutting *State-of-the-art:* TRL 9 *Limitations/Challenges:* ○ Production speed is not fast enough for high volume applications ○ Handling and positioning the preform are challenges with fiber placement at high throughput ○ Heat transfer can be a rate limiting process step
5. Weaving, stitching, braiding, mat processes *Application Areas:* Cross-cutting

State-of-the-art: TRL 9
Limitations/Challenges:
- Current placement methods are expensive and too slow for high volume production
- Development of in-situ process steps to make complex parts is an opportunity
- Current weaving technology is limited; there are opportunities for advancements

6. **Fiber injection molding, direct long fiber thermoplastic (D-LFT)**
   Application Areas: Automotive
   State-of-the-art: TRL 9
   Limitations/Challenges:
   - Limited part size and complexity are limited with this process
   - Limited tool life due to abrasion from the fibers
   - Limited fiber lengths (depending on technology) can be used with this process
   - The process has limitations for fiber placement, which impacts part performance due to sub-optimal fiber orientation
7. **Long fiber thermoplastic (LFT) overmolding**
   Application Areas: Automotive
   State-of-the-art: TRL 5
   Limitations/Challenges:
   - Generates undesired waste material
   - Long cycle times limit use for high volume production
   - Lack of compatibility between resins limits use of this process
8. **Traditional additive manufacturing processes – Fused Deposition Modeling (FDM) with fibers**
   Application Areas: Cross-cutting
   State-of-the-art: TRL3
   Limitations/Challenges:
   - Incorporating the fiber into the additive process is challenging
   - Speed of production and size of parts are currently limited with additive processes
   - Processes have limited accuracy in fiber placement
9. **Cure on demand (COD) technologies**
   Application Areas: Cross-cutting
   State-of-the-art: TRL Low
   Limitations/Challenges:
   - Limited applications for this process today
10. **Rapid volumetric heating methods (e.g., microwave curing)**
    Application Areas: Cross-cutting
    State-of-the-art: TRL 5-9
    Limitations/Challenges:
    - Capital equipment is expensive and limits technology use
    - Unique process tools are needed, the applicator has to be designed to the part, adds complexity

Manufacturing Process Technologies – Blue Team B

Table 1 presents Blue Team B participants' comments regarding key manufacturing process technologies, application areas for those technologies, the state-of-the-art, and the limitations and challenges facing the technology today.

Table 1. Summary of Blue Team B participants' comments related to manufacturing process technologies.

Key Technologies
1. External field/alternative thermal cure (e.g., microwave, magnetic field, induction heating, spot/in-situ with fiber steering) *Application Areas:* Cross-cutting; with AFP for storage tanks *State-of-the-art:* ○ Basic research, applied research level *Limitations/Challenges:* ○ Capital equipment is expensive and limits technology use ○ Final part properties are not the same using alternative cure methods as with traditional processes ○ Coupling and formulation issues with resins, need to modify to use resins with these processes ○ Cure kinetics is a limitation, have to hold temperature to achieve crystallinity, makes the process slower ○ Heating uniformity using alternative cure technology is a challenge
2. Non thermal cures (e.g., photodynamic, ultraviolet, moisture) *Application Areas:* Cross-cutting *State-of-the-art:* ○ Basic research, applied research level for most ○ Ultraviolet is commercially available *Limitations/Challenges:* ○ Catalysts are expensive could increase final cost ○ Thermal properties parts made with non-thermal cure processes are lower compared to those made using traditional processes ○ Changes and optimization of resin formulations for these techniques are needed adding complexity and cost ○ Achieving full cure with carbon fiber composites is challenging as penetration depth can be limited ○ Thermal run-away in cure is a challenge and would need chemistry modifications in the materials to help address the problem
3. High speed molding processes (e.g., resin transfer systems and compression molding) *Application Areas:* Cross-cutting *State-of-the-art:* ○ Demonstration level for carbon fiber tanks ○ Commercial for automotive (can get to 100,000) *Limitations/Challenges:* ○ Can achieve production volume with short fibers using these processes but will not have high performance properties needed

- Limitation is preforming for long fibers

4. **Automated tape placement (ATP) and automated fiber placement (AFP)**

Application Areas: Good for large, complex parts; good for tanks and wind

State-of-the-art:
- Fiber steering, can orient axially
- Spot cure is state-of-the-art
- 2800in/min (thermoset) (comment: rather than in/min rate, it is better represented as kg/hr)

Limitations/Challenges:
- AFP is limited by production speed, especially for in-situ consolidation
- This process is limited for smaller sized parts, more suitable for large parts
- Capital intensive process equipment
- Thermoplastic fiber placement is limited
- **Use of wider fabrics creates a challenge – how to get the fabric to lay in the mold,** have to slit material **which increase**s cost
- Current tape materials are not designed for alternative cure methods
- Holding dry fabrics in place is a process challenge
- High waste produced, opportunities to minimize trim waste
- Could utilize co-mingled fabrics and have tailored fiber placement in localized areas as one way to improve process

5. **Tooling – flexible, rapid, no tooling**

State-of-the-art:
- Invar and bismaleimide (BMI) are the standard tool materials
- Flexible tooling early stage
- No tooling – early stage (basic/applied); ways to use additive for tooling also early stage

Limitations/Challenges:
- New ceramic materials for tooling have not been proven
- Tooling materials are not thermally optimal for autoclave processes
- Tooling system can be expensive
- Tooling processes can be wasteful, for example there is minimal use of reusable technology like bags

6. **Pultrusion**

Application Areas: For wind spar caps, good for stringers/support structures, and frame rails, flat beds for heavy trucks

State-of-the-art:
- Applied research/demonstration (epoxy-carbon fiber and glass-epoxy)
- 5-6 feet/minute with polyesters (3 feet/minute with epoxies)

Limitations/Challenges:
- Use of pultruded parts would requires joining of the pultruded part to other components which can be a challenge
- Joining pultruded parts to other structures using mechanical attachments creates potential failure points (the drilled holes) and would require inserts to address the weaknesses created which adds cost and complexity to assembly

7. **Joining**

Application Areas: Multi-material vehicles; Wind; Cross-cutting

State-of-the-art:
- Thermoset to thermoset for bonded joining

- Thermoplastics composites with a thermoplastic injection molding process
- Resin Transfer Molding (RTM)/fusion; can compression mold on top for surface qualities

Limitations/Challenges:

- Joining **thermoset composites to metals is challenging, joining any material to thermoplastic** composites is particularly challenging
- Control of thermal expansion (CTE) mismatch is challenging
- Bonded joint diagnostics, especially on blind joints, are limited
- Surface geometry (variability of parts) and preparation technologies are limited

8. Design modeling and simulation (M&S)

Application Areas: Cross-cutting

State-of-the-art:

- There are kinetic based simulations (autoclaves, fiber simulations) in development that can allow distorted part simulation and look at thermal distribution to the part; only a few available are good quality

Limitations/Challenges:

- Don't understand opportunities for ATP/AFP fiber steering, especially incorporating these into the overall design
- Lack of modeling and simulation for joining, especially joining of dissimilar materials
- Design practices for composites today do not account for manufacturability and reuse
- Thermoplastics can be recycled and reused, need better waste management practices to be successful (keep the types of different materials separated and sorted so they can be reused)
- Many modeling and simulation tools lack sufficient experimental validation
- Design tools and practices do not account for uncertainty in manufacturing processes

Additional comments from participants captured in the "Parking Lot" of this breakout session are summarized below:

- A challenge question for the community more broadly: how can we do a better job of integrated processing? For example, combining filament winding to make a preform, with thermoforming (for thermoplastics) to make an integrated process.
- A key point is that composites have to be designed for manufacturability to maximize the benefit of composite performance; we are not just designing a replacement for a metal part.
- There is a general lack of maturity in composite manufacturing technology.
- Coatings to enable painting of thermoplastics could enable further use of this technology.
- Intermediate forms with hybrid metal-composite constituents (pellets, mat, tapes, innovative waves, and foams) could respond to heating/cooling in a tool more quickly and enable faster processing times.
- Improvements in fiberglass sizing chemistry to improve laminate properties could enhance use of fiberglass.

Enabling Technologies and Approaches – Red Team

Table 1 presents the Red Team participants' comments regarding key manufacturing process technologies, application areas for those technologies, the state-of-the-art, and the limitations and challenges facing the technology today.

Table 1. Summary of the Red Team participants' comments related to enabling technologies and approaches.

Key Technologies

1. **Design, modeling, simulations, optimization (including tooling design)**
   Application Areas: For non-aerospace applications
   State-of-the-art:
   - Design informed by manufacturing, such as those that use pattern recognition analytics (Artificial Intelligence-like models)
   - Physics based models
   - Large assumptions and approximations are still being made
   - Aerospace tends to focus on thin wall structures
   - Numerous iterations are required today; tools that span materials scales is an opportunity
   - Models are often limited and not available or accessible on the shop floor for composite manufacturing

   Limitations/Challenges:
   - Alignment of the composites technology community is a challenge; difficult to harmonize challenges of the aerospace and automotive industries
   - Synergistic effects (i.e., effect of sustained stresses, pH, temperature, etc.) are not well understood for nonlinear, multi-variable problems – cannot afford to make gross approximations; the ability to quantify response mechanisms is an opportunity
   - Limited technicians, infrastructure, and repair sensing technologies available (e.g., body shops for vehicles)
   - There is a trade off between integrated structures vs. modular structures that should be considered when designing composites structures
   - For monocoque designs, every part becomes expensive making structural repair a huge enabling resource
   - Timeframe to meet goals mentioned in RFI over ten year time period are aggressive
   - There is an opportunity for better techniques to develop composite tooling; a tooling paradigm shift to a shorter timeframe could help technology adoption
   - Currently there is insufficient knowledge to simulate failure and degradation of composites

2. **Databases and standards**
   State-of-the-art:
   - A lot of data available from aerospace; reinforced plastics data is available but may not have been captured
   - Composites Handbook 17 (former Mil Handbook 17) is a good source of composite data and design practices

   Limitations/Challenges:
   - Industry will not invest in technology development for qualification and the cost to certify parts
   - No clear guidance or standards for repair and maintenance (composites with self-healing

properties may help solve the repair issue)
  - Lack of open datasets at all material length scales (micro to macro)
  - Statistical failure databases from industry would benefit technology development
  - Techniques for complete materials characterization (including fiber length) are lacking
  - Data coordination for existing technology and incorporating new information is poor

3. **Sensing and measurement**

   State-of-the-art:
   - Sensors are not well integrated with data or manufacturing processes

   Limitations/Challenges:
   - Use of intelligent sensors is minimal – distributed sensors linked to data and physics, integrated with manufacturing and embedded in structures is an area of opportunity (i.e., multifunctional material)
   - Self-diagnosing materials are an area of opportunity, i.e., color change or a “check engine light” for composite structures
   - Sensing technologies, especially for joints is limited
   - Nondestructive testing at the point of manufacture is an area of opportunity
   - Data Mining/Data Informatics – the composites community could be better prepared for “big data” from sensors; use of actual process data to inform design may be able to replace need for some modeling and simulation
   - Nondestructive tools to certify and requalify composites are lacking; the ability to predict the lifetime of composite parts could advance the technology

4. **Training**

   State-of-the-art:
   - Costs $50,000 per year to train a graduate student
   - Professional training and development for composites and composite manufacturing is lacking
   - There is little understanding of anisotropy – directional characteristics of materials today

   Limitations/Challenges:
   - Takes a long time to train people
   - Opportunity to engage community colleges as well as colleges/universities

Additional comments from participants captured in the “Parking Lot” of this breakout session are summarized below:

- Look for opportunities where composites provide totally new capabilities than what are currently available. Value-add, rather than just reduced cost, faster production, etc.
- Another broad challenge is that once a toolset (simulation model) is developed, the time, testing, labor, and cost to fill out the fiber characterization material properties (in situ properties) in that toolset is enormous.
- Composites industry is diverse and that makes it challenging for the industry to collaborate. There are many fibers, many resins.
- Industrial consolidation and focus, similar to the model of the steel industry, could benefit the composites industry.
- Nanofibers and other nanomaterials are areas of opportunity.
- One potential way to reduce cost is through cheaper fiber or reducing the fiber volume fraction.

- Multifunctionality is an area of opportunity for expanding potential for composites.
- Integrated structural demonstrations to focus efforts and validate simulations are an area of opportunity.
- Higher density material transportation, enabled by higher pressure storage, can reduce cost, emissions, energy use, etc.

Recycled and Emerging Materials – Green Team

Table 4 presents Green Team participants' comments regarding key manufacturing process technologies, application areas for those technologies, the state-of-the-art, and the limitations and challenges facing the technology today.

Table 4. Summary of the Green Team participants' comments related to recycled and emerging materials.

Key Technologies

1. **Bio-derived/cellulosic sugars converted by a microorganism to end products (for non-aerospace applications)**
   Application Areas: Reinforced fibers (bio-PAN), resins, other chemicals (PLA)
   State-of-the-art:
   - Organism development for chemical production are probably TRL 3; from corn-probably commercial scale sugar production, but not yet from cellulosic
   Limitations/Challenges:
   - Organism development is challenging
   - Process development is also limiting
2. **Nanocellulose: cellulose nanocrystals and microfibrils, as well as synthetically derived nanocellulose**
   Application Areas: Undetermined – see challenges below
   State-of-the-art:
   - Nanocrystal processing is TRL 5-6, e.g., from cellulose-to-ethanol process, recalcitrant material remaining is nanocrystals/microfibrils
   - Companies are producing synthetically derived nanomaterials at kilogram quantities (TRL 4-5)
   - One advantage of cellulosic material is that it is non-toxic
   Limitations/Challenges:
   - **Identification of applications and markets for these materials**
   - **Making fibers compatible with processes that have consistent size and can be incorporated into polymer matrices**
   - Need to remove water because nanocellulose is hydrophilic, which is a separations challenge
3. **Lignin/lignin-polyacrylonitrile (PAN) blends**
   Application Areas: Melt-spinning carbon fiber (for continuous processing)
   State-of-the-art:
   - TRL 3
   Limitations/Challenges:
   - Current lignin cost, low value material
   - Need to start with the right type of lignin, as there are highly variable properties based on species, processing and environment
   - Transforming lignin to materials with desired properties is challenging
   - Biological preprocessing using organisms
   - There is a lack of appropriate chemical catalysts, would require catalyst development adding cost and complexity

4. **Recycling/recyclability**

   Application Areas: Cross-cutting

   Limitations/Challenges:
   - Recycled materials have to be reliable in terms of quantity, quality, cost, etc.
   - Purpose and target use of recycled materials needs to be better understood in order to downgrade materials, develop and understand the supply chain, and design products for recyclability
   - Service life issues, including life cycle and other impacts, are not well understood for recycled or repurposed composites
   - Lack of understanding of how long material will realistically last compared to how material will be used
   - Intermittent and variable supply of recycled materials leads to business risk for the recycler

Additional comments from participants captured in the "Parking Lot" of this breakout session are summarized below:

- Goal of recycling is not to make 100% recycled material; the benefits of recycling include recovery of some of the embedded energy.
- For improvements in recycling, we need to identify the potential uses for recycled material (perhaps with lower performance requirements) and the requirements for those applications.
- Without knowing the potential uses for recycled materials, how reasonable are the targets? It is difficult to determine.
- A general comment: the targets and discussion was focused on carbon fiber. How does this apply to other types of fibers (i.e., glass)?

Additional Technologies

Participants presented technologies that were not discussed in further detail in their breakout group due to time limitations. The technologies not discussed from all breakout groups are listed below:

Technology	Application Areas
Additive manufacturing (e.g., powder bed fusion) for fast complex, low coefficient of thermal expansion (CTE) molds for composites	Automotive
Automated/robotic methods in general	Cross-cutting
3D weaving (enable joining of composite to reduce part count)	Cross-cutting, TRL 5-6, cost too high to compete with fastening
Assess value proposition of adding nano-particles and nanotubes to FRC resins	Cross-cutting
Autoclave alternative processes (for prepreg laminates and sandwich structures)	Cross-cutting
Automated placement of tackified preform	Wind
Braiding and pultrusion	Piping
Combine topological design and processing technology	Cross-cutting
Compression molding SMC	Automotive
Creep-resistant recycled RFPs through new reinforcement strategies and models	Cross-cutting
Double diaphragm forming, membrane forming of prepreg laminates and sandwich structures	Cross-cutting
Extrusion/mixing + injection molding	Automotive and Aerospace
Fiber/metal laminates	Not Provided
Filament winding with low-cost carbon fiber	Natural gas (lightweight pressure vessels for large-scale transportation of wasted natural gas; storage tanks for trucks/buses, energy storage, low-cost pressure tanks for hydrogen
Filament/tape winding with low-cost carbon fiber/glass	Cross-cutting
Graphene-reinforced nanocomposites, functionalized through mechanical exfoliation combined with polymer processing in single step	Automotive, Aerospace, Defense
Hybrid hierarchical multi-scale reinforcement, design/process integration	Cross-cutting
High speed thermoset compression molding	Cross-cutting
High temperature infusion (batch process, rapid curing)	Housing/infrastructure
High throughput, precision automation	Wind
Hybrid carbon-glass fiber or carbon-metal composites	Cross-cutting
Improved reinforcements	Cross-cutting
Improved resin systems	Cross-cutting
Infusion	Wind
Injection molding BMC/thermoplastics	Automotive
In-situ resin mixing	Cross-cutting

Insurance industry inclusion and use of decreased safety factors	Cross-cutting
Integrated sensors in long profiles	Natural gas
Innovative structural sandwich construction design and manufacturing	Cross-cutting
Inverse flame processing for layered composites (open air layering)	Aerospace
Inverse flame processing for layered composites (open air layering)	Defense
LFT overmolding (directional preforms)	Automotive
Liquid molding	Automotive
Low cost fiberglass/polyurethane foam preforms	Structural (wind)
Modeling of random fiber composites	Cross-cutting
Modeling performance of carbon fiber/glass blends	Cross-cutting
Multi-material systems	Cross-cutting
Out of autoclave	Cross-cutting
Oven vacuum bag	Wind
Polyurethane prepreg sheets	Structural (Wind), TRL 4-5
Pultrusion	Automotive
Pultrusion of spar/stiffeners	Wind
Pultrusion processes	Cross-cutting
Rapid cure polymer matrix systems	Cross-cutting
Rapid Joining for dissimilar materials	Automotive
Rapid, integrated dry fiber preforming (for subsequent liquid molding)	Cross-cutting
Simulation of thermoforming to link manufacturing to structural properties	Cross-cutting
Stamping up thermoplastics	Automotive
Thermoforming	Automotive
Thermoforming of fabrics (woven, unidirectional, stitched)	Automotive and Aerospace
Thermoplastic overmold technology	Automotive
Thick textile fabric/preform	Wind
Tow/tape placement of OOA thermosets and thermoplastics	Aerospace
Tunable polymers using nano-reinforcement (used with continuous fiber or additive manufacturing for complex shapes)	Automotive
Ultrasonic molding	Automotive
Understanding formation of defects during manufacturing	Cross-cutting
Unidirectional-tape slitting/spooling for AFP	Automotive, TRL 7-9, cost is very high
Using fungal mycelium to bind agricultural waste into low-cost bio-composites and resin infusion preforms	Cross-cutting
Vibrational molding	Automotive

Appendix 1: Participant List

Fiber Reinforced Polymer Composite Manufacturing Workshop

Hilton Crystal City – Arlington, VA
January 13, 2014

Ronald Adams	Jushi USA
Jim Ahlgrimm	U.S. Department of Energy
John Arimond	University of Maine
Michael Bahleda	Bahleda Management and Consulting, LLC
Jacob Barker	Composite Technology Development
Robert Barsotti	Arkema Inc.
Dan Beattie	Dow Chemical
Derek Berry	National Renewable Energy Laboratory
Craig Blue	Oak Ridge National Laboratory
Raymond Boeman	National Advanced Composites Manufacturing Institute
Nicola Bowler	Iowa State University
Scott Boyce	The Dow Chemical Company
Dane Boysen	ARPA-E
Andrew Brink	Michelman
Dale Brosius	Quickstep Composites, LLC.
Ron Brown	Agenda 2020 Technology Alliance of the Forest Products Industry
John P. Busel	American Composites Manufacturers Association
Isaac Chan	U.S. Department of Energy
Fu-Kuo Chang	Stanford University
Fangliang Chen	Columbia University
Quanfang Chen	University of Central Florida
Katy Christiansen	AAAS Fellow - U.S. Department of Energy, Note Taker
Joe Cresko	U.S. Department of Energy, Facilitator
Fred Crowson	Energetics Incorporated, Facilitator
Lynn Daniels	U.S. Department of Energy, Note Taker
Robert Davies	Fibrtec Inc.
Tom Dobbins	American Composites Manufacturers Association
Christopher Duston	Case Western Reserve University
Bill Dykstra	Temper, Inc.
Cliff Eberle	Oak Ridge National Laboratory
Kevin Elsken	Bayer Material Science LLC
Ryan Emerson	PPG Fiberglass S&T
Jeffrey Florando	Lawrence Livermore National Laboratory
Douglas Freitag	Bayside Materials Technology
Peter Fritz	Eaton Corp
Hota GangaRao	West Virginia University
Frank Gayle	NIST
Nicholas Gianaris	Composite Vehicle Research Center-Michigan State University
John Gillespie Jr.	Center for Composite Materials
Alison Gotkin	United Technologies Research Center
Christopher Gouldstone	N12 Technologies
Thomas Hager	Owens Corning
Christopher Hansen	University of Massachusetts Lowell
David Hardy	U.S. Department of Energy
Clarissa Hennings	Ingersoll Machine Tools, Inc.
Gregory Hickman	Boeing Research & Technology
Paul Hirsh	American Composites Manufacturers Association
Paul Honka	Beacon Power
Dustin Horning	McAllister & Quinn, LLC
John Hryn	Argonne National Laboratory
Warren Hunt	Nexight Group, LLC
Robert Hutchinson	Rocky Mountain Institute
Marc Imbrogno	The Composites Group
Joe James	Agri-Tech Producers, LLC
Danize Jean Simon	Self
Gefu Ji	Louisiana State University

Mark Johnson	U.S. Department of Energy
Ken Johnson	Pacific Northwest National Laboratory
Lynne Krogsrud	Tank Automotive Research Development Engineering Center (TARDEC)
Avanti Lalwani	Duramold, Inc.
Bruce LaMattina	Rutgers, The State University of New Jersey
Scott Lewit	Structural Composites, Inc.
Ted Lynch	Strategic Marketing Innovations, Inc.
Michael Maher	DARPA
Blake Marshall	U.S. Department of Energy, Facilitator
Jeffrey McCay	Composite Applications Group
Steve McKnight	National Science Foundation
Scott McWhorter	Savannah River National Laboratory
Theresa Miller	Energetics Incorporated, Note Taker
Amit Naskar	Oak Ridge National Laboratory
Brian Naughton	Sandia National Laboratories
Elizabeth Nesbitt	U.S. International Trade Commission
Grace Ordaz	U.S. Department of Energy, Facilitator
Donald Osment	TenCate Advanced Composites
Ronald Ott	Oak Ridge National Laboratory
Stephen Parsons	Lockheed Martin Aeronautics
Joel Pawlak	NC State University
Assimina Pelegri	Rutgers, The State University of New Jersey
Mike Peretti	GE Aviation
William Peter	Oak Ridge National Laboratory
Frank Peters	Iowa State University
R. Byron Pipes	Purdue
Donald Radford	Colorado State University
Cheryl Richards	PPG Industries, Inc.
Rani Richardson	Dassault Systemes
David Ring	Strongwell
Greg Rucks	Rocky Mountain Institute
Marty Ryan	SCRA
Karana Shah	Dixie Chemical
Devanand Shenoy	U.S. Department of Energy
James Sherwood	University of Massachusetts Lowell
Dong-Jin Shim	GE Global Research
Kunigal Shivakumar	North Carolina A&T State University
Mark Shuart	U.S. Department of Energy, Facilitator
Stephen Sikirica	U.S. Department of Energy, Facilitator
Kevin Simmons	Pacific Northwest National Laboratory
Neel Sirosh	LightSail Energy
Mike Soboroff	Rock Creek Strategies
Lanetra Tate	NASA
Rebecca Taylor	NCMS
Tony Tubiolo	Note Taker
Uday Vaidya	University of Alabama at Birmingham
Jeff Vervlied	Hall Composites
John Vickers	NASA
Pv Vijay	West Virginia University
Kelly Visconti	U.S. Department of Energy, Facilitator
Daniel Walczyk	Rensselaer Polytechnic Institute
Michael Wang	Argonne National Laboratory
Paula Watt	The Composites Group
Elizabeth Wayman	U.S. Department of Energy
Kirste Webb	Visionary Solutions, LLC
Staci Wegener	BASF Corporation
Randall Weghorst	AOC
Geoffrey Wood	Profile Composites, Inc.
Andrew Wright	Polsinelli
Amanda Wu	Lawrence Livermore National Laboratory
Amy Wylie	Bayer Material Science
Sean Xun	New West, Facilitator
Ozlem Yardimci	PRAXAIR INC.
Shridhar Yarlagadda	University of Delaware
Huiming Yin	Columbia University
Corinne Young	Corinne Young LLC
Xiong Yu	Case Western Reserve University
Wenping Zhao	United Technologies Research Center

Appendix 2: Agenda and Pre-Read Material

Fiber Reinforced Polymer Composite Manufacturing Workshop Agenda

Hilton Crystal City – Arlington, VA
January 13, 2014

Time (EDT)	Activity	Speaker
8:30am – 9:00am	***Registration***	
9:00am – 9:05am	*Welcome and Introduction*	**Mark Johnson** Director, Advanced Manufacturing Office
9:05am – 9:20am	*Clean Energy Manufacturing Initiative*	**David Danielson** Assistant Secretary DOE Office of Energy Efficiency and Renewable Energy
9:20am – 9:50am	*Advanced Manufacturing Office Overview and Review of RFI Results*	**Mark Johnson** Director, Advanced Manufacturing Office
9:50am – 10:30am	*Panel Discussion: DOE Perspectives*	**Mark Shuart**, Advanced Manufacturing Office (Moderator) **Jim Ahlgrimm**, Wind and Water Office **Jerry Gibbs**, Vehicles Technology Office **Scott McWhorter**, on behalf of Fuel Cells Technology Office **Dane Boysen,** ARPA-E
10:30am – 11:00am	***Break – On Your Own***	
11:00am – 11:20am	*AMP 2.0 and Federal Manufacturing Activities*	**Frank Gayle** Deputy Director - Advanced Manufacturing National Program Office
11:20am – 11:50am	*Inter-Agency Perspectives*	**Steve McKnight**, NSF **John Vickers**, NASA **Mick Maher**, DARPA
11:50am-12:00pm	*Breakout Instructions*	**Mark Johnson**
12:00 pm – 1:30 pm	***Lunch – On Your Own***	
1:30pm – 3:45pm	**<u>Breakout Sessions – 4 Groups</u>** **Blue Team A – Manufacturing Process Technology** Facilitators - Joe Cresko and Sean Xun; Note taker – Lynn Daniels **Blue Team B – Manufacturing Process Technology** Facilitators - Kelly Visconti and Steve Sikirica; Note taker – Theresa Miller **Red Team - Enabling Technologies and Approaches** Facilitators - Mark Shuart and Fred Crowson; Note taker – Tony Tubiolo **Green Team - Recycled and Emerging Materials** Facilitator - Blake Marshall and Grace Ordaz; Note taker – Katy Christiansen	
3:45pm – 4:00pm	***Break – On Your Own***	
4:00pm – 4:30pm	*Report Outs* *Closing Remarks*	Rapporteurs Mark Johnson

Additional Information Provided with the Agenda to Prepare Participants

Objectives of the Workshop:
Through the workshop AMO seeks to foster an exchange of information among industry, academia, research laboratories, government agencies, and other interested parties on technical issues and manufacturing challenges related to achieving low cost Fiber Reinforced Polymer Composites and impact US manufacturing competitiveness and energy. The workshop will include presentations by government personnel as well as facilitated breakout sessions to gather input from participants. AMO intends to discuss the comments received as a result of two recent Requests for Information (RFI) on this topic.

Objectives of the Breakout Discussion:
Through the Requests for Information released by AMO, broader challenges and potential objectives for composite manufacturing to have an impact on key clean energy and industrial applications such as wind turbines, lightweight vehicles and compressed gas storage, among others were identified.

In the breakout sessions, EERE would like to gather feedback and foster a discussion regarding the state-of-the-art and technical challenges. Let’s go deeper into:

- Manufacturing Process Technologies - Blue Teams A and B (e.g., lay-up techniques, out of the autoclave, novel cure techniques, resin infusion, pultrusion, sheet molding compound, tooling, machining)
- Enabling Technologies and Approaches - Red Team (e.g., design methods and databases, analytical tools, nondestructive evaluation, damage tolerance, joints, repair, other)
- Recycled and Emerging Materials - Green Team (e.g., recycling carbon fiber, renewable precursor materials, advanced glasses, nanomaterials)

DOE has proposed four objectives for fiber reinforced polymer composite manufacturing: reduction of production costs; reduction of life cycle energy and greenhouse gas emission; reduction of embodied energy and associated greenhouse gas emission; and demonstration of innovative recycling technologies at sufficient scale.

Within the context of the focus area for your group and with respect to the potential objectives for composites manufacturing as outlined in the DOE RFI, to have impact on clean energy and industrial applications to: 1) reduce cost, 2) increase production rate, 3) lower energy and 4) increase recyclability of fiber reinforced polymer composites. In the breakouts we seek to identify and discuss:

- Key technologies that have the potential to help achieve these objectives, as well as the target application area or cross-cutting technologies.
- State-of-the-art for the identified technologies as well as Technology Readiness Level/Manufacturing Readiness Level (TRL/MRL).
- Key current limitations/challenges for each technology, particularly for use in clean energy an industrial applications.

Breakout Discussion Ground Rules

- No speeches.
- Listen to each other.
- Suspend judgment.
- Challenge ideas, not people.
- Not here to reach consensus, everyone to provide individual thoughts.
- There will be times you have more to contribute and times you will have more to learn.
- Check your "logo" at the door - speak from your expertise and experience.
- Go a layer deeper, when possible be specific.
- Will need to focus, realizing there are many technologies – which could be most impactful?
- This will not be a fully detailed "roadmap" exercise; it is likely we will not get to everything. Notecards will also be available to submit thoughts and inputs throughout the discussion that you want to make sure are captured.

Introductions and Kick Off (~20mins)

- Walk through the breakout objectives and ground rules with the group.
- We will review the framework and report out slide format.
- We will start the session with a brief introduction around the room – your name and organization, so we can all get to know one another better.
- Participants who have submitted their 1 slide discussion starter will be invited to speak for 1-2 minutes to seed the discussion.

Brainstorming and Focusing (~40 mins)

- Take a few minutes to write down ideas on notecards, then open the floor for discussion:
    - *Identify a specific key technology that has the potential to help achieve these objectives and the target application areas or whether the technology is cross-cutting.*
- The facilitator will gather notecards and group similar ideas on the wall.

Short Break (~5 mins)
Going Deeper (~50 mins)

- Going through each of the technologies identified, we will spend some time discussing responses to the following questions:
    - *What is the state-of-the-art for this technology? Notional Technology Readiness Level/Manufacturing Readiness Level (TRL/MRL) - basic research, applied, pilot scale, commercial?*
    - *What are the current limitations/challenges to this technology, in particular for use in clean energy and industrial applications?*
- Notecards will be placed on the wall for each technology as the discussion progresses. After 5-10 minutes, we will move onto the next technology, allowing for additional points to be added to the wall in the last 15 minutes.

Review and Close (~15 mins)

Near the end of the discussion time, the facilitators will review the captured notes on the wall with the group, allow additional cards to be added and then during the break translate information into the slide for report out.

Fiber Reinforced Polymer Composite Manufacturing Workshop: Summary Report

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE/EE-1041 • January 2014
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