U.S. Composites Manufacturing Industry

Technical Roadmap

By

Facilitating Industry by Engineering, Roadmapping and Science (FIBERS) Consortium

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List of Abbreviations

ACC	Automotive Composites Consortium
AFP	Automated Fiber Placement
AMTECH	Advanced Manufacturing Technology Consortia
ATL	Automated Tape Laying
ASTM	American Society for Testing and Materials
BMC	Bulk Molding Compound
BNNT	Boron Nitride Nanotubes
CAFE	Corporate Average Fuel Economy
CAIIACC	Consortium for Accelerated Innovation and Insertion of Advanced Composites
CCT	Certified Composite Technician
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CNT	Carbon Nanotube
DARPA TRUST	Defense Advanced Research Project Agency TRUST in Integrated Circuits
DoD	Department of Defense
EPD	Environmental Product Declaration
FIBERS	Facilitating Industry by Engineering, Roadmapping and Science
GFRP	Glass Fiber Reinforced Polymer
HAP	Hazardous Air Pollutants
IACMI	Institute for Advanced Composites Manufacturing Innovation
IP	Intellectual Property
ISO	International Standardization for Organization
LCI	Life-Cycle Inventory
MEP	Manufacturing Extension Partnership
NDE	Nondestructive Examination
NIST	National Institute of Standards and Technology
NNMI	National Network for Manufacturing Innovation
OoA	Out of Autoclave
OSHA	Occupational Safety and Health Administration
PAN	Polyacrylonitrile
QA/QC	Quality Assurance / Quality Control
RD&D	Research, Development and Deployment
RRIM	Reinforced Reaction Injection Molding
RTM	Resin Transfer Molding
SAMPE	Society for the Advancement of Material and Process Engineering
SMC	Sheet Molding Compound
SME	Small and Medium-Sized Enterprises
SOP	Standard Operating Procedure
SPC	Statistical Process Control
UV	Ultraviolet
VIP	Vacuum Infusion Processing
VOC	Volatile Organic Compound

EXECUTIVE SUMMARY

This report provides an overview the findings of the FIBERS roadmapping activities related to processing methods, materials, predictive modeling and workforce development. The FIBERS team explored the current state of the industry and the vision for the future through a set of well-connected roadmapping activities. Three sectors were identified as offering the greatest near-term growth opportunities for composites: Automotive, Infrastructure and Aerospace. The growth in each of these sectors will require widespread use of automation to meet the high-volume, low-cost requirements of each of these sectors. Automation and cycle-time production will require research and development into new quick-curing resins and forming processes. The new resins and processes will drive the increased use of modeling to explore in a virtual environment how these innovations will impact composite manufacturing processes. While the marine, wind, and sports and recreation sectors can continue to grow, it is not anticipated that growth in these sectors will be as significant. However, all sectors should benefit from the advancements in materials, processing, automation, modeling and workforce development that will be led by the auto, infrastructure and aerospace sectors.

Four grand challenges to the growth of the U.S. Composites manufacturing industry were identified through the roadmapping activities. These include (1) the development of a well-trained and sufficiently-sized workforce, (2) the reduction of the cycle time for part production, (3) the expansion of the knowledge and access to the tools that enable manufacturers and designers to use new processing methods and materials, and (4) the advancement of the material performance.

The most significant logistical barrier to growth of the US composites manufacturing industry is workforce development. The future of composites manufacturing is one in which new college graduates enter the workforce with a broad, relevant and up-to-date knowledge of composites manufacturing methods and materials. Efforts must be pursued to inform K-12 students about the role of composites in society and career opportunities. Companies need to develop and support co-op and internship programs for AS, BS, MS and doctoral engineering students. Each partnering education institution must have personnel motivated to establish these pathways and programs, who are actively engaged with and responsive to their industrial counterparts. Thus, the workforce development challenge provides the opportunity for academics to work with industry, government and non-profits to develop outreach activities, education programs and work experiences to develop the future generations of composite manufacturing technicians and engineers.

The most significant and wide-reaching technical challenge is reduction in cycle time and process variability. This challenge is an opportunity for the researchers to develop new and innovative manufacturing processes. These innovations will require a fundamental understanding of the physics associated with a processing method and access to modeling tools that can explore how changes in process conditions influence throughput and part quality. These innovations can be realized most efficiently if companies can learn to work together for the overall benefit of the composites manufacturing industry. Unlike some industries that recognize the benefits of

research collaboration, fears about intellectual-property protection are forcing many parties along the composites manufacturing supply chain to duplicate research and development investments or to use outdated processes and approaches. Smaller firms are also faced with limited to no access to new equipment and analysis capabilities, thereby limiting their ability to explore and justify the cost of new-process adoption. Companies need to come together and work with academia to be proactive in encouraging the federal government to make significant investments to support fundamental research collaborations in composite manufacturing. The Institute for Advanced Composites Manufacturing Innovation (IACMI) is playing a major role in taking fundamental research results into composite manufacturing demonstration projects, but there needs to be a process for sustaining a pipeline to develop and deliver new material systems, innovative processing techniques and advanced modeling that will fuel future advances in composites manufacturing.

Modeling tools are a valuable resource for investigating new composite designs and new processing methods. These tools provide manufacturers a virtual environment to redesign existing processes or to add new processes that can facilitate improvements in the manufacturing process. Unfortunately, these tools are often underutilized for such reasons as limited access to the tools, lack of qualified personnel with experience in using the tools, or lack of awareness that the tools even exist. The objective to decrease product development costs while improving performance compared to existing composite and metal products is the driving need for development of improved predictive tools and for increasing their use across the industry. The widespread adoption of predictive modeling tools faces challenges that include the lack of material data inputs and of a general recognition of the advantages that can be gained from such modeling. The implementation of demonstration projects and initiatives, which include the use of predictive modeling tools, can educate industry about the capabilities of these tools and show their value in expediting the design of manufacturing processes. Thus, there are vast opportunities with respect to (1) making the current modeling tools available to SMEs and for the development of new and improved modeling tools, (2) training engineers how to use the tools, and (3) the building of a comprehensive database of material properties.

Overall, the U.S. Composites Manufacturing industry is strong; however, the roadmapping activities identified opportunities for significant increased penetration of composites across all sectors. These opportunities span the range from workforce training programs to technical innovations in manufacturing processes, materials development and modeling. Industry, academia, government and non-profits must collaborate on demonstration projects and initiatives to realize these opportunities. Collaborations such as IACMI are positioned to address some of the industry’s challenges. Industry and government must support these and further efforts to address all of the identified Grand Challenges.

1. INTRODUCTION

Growing U.S. composites manufacturing requires strategic planning based on input from all of the key stakeholders. In 2014, the National Institute of Science and Technology (NIST) funded a roadmapping project critical to that growth and the FIBERS Consortium (Facilitating Industry By Engineering, Roadmapping and Science) was established.

The FIBERS consortium is led by five U.S. universities with composites manufacturing expertise: Iowa State University, Rensselaer Polytechnic Institute, University of Delaware, University of Massachusetts Lowell and University of New Hampshire. These universities have worked with many large companies, as well as small- and medium-sized enterprises (SMEs) across the supply chain – from raw materials to field-service applications – to compile a comprehensive roadmap of growth opportunities and challenges within the U.S. composites manufacturing industry. The ACMA has also been a key player, working hand-in-hand with the FIBERS Consortium to facilitate its mission of developing a comprehensive roadmap of the current state of composites manufacturing in the U.S., the barriers facing the future growth of the industry and opportunities for demonstration projects that can address overcoming those barriers.

To understand the U.S. composites industry and to develop a sound growth strategy, the FIBERS team explored the current state of the industry and the vision for the future through a set of well-connected roadmapping activities that included online surveys, regional sector-specific workshops, site visits to manufacturing facilities and participation in professional conferences. A list of these activities is provided in Appendix A.

Industry surveys conducted by the FIBERS Consortium in 2014 and 2015 identified the top three sectors for offering the greatest growth opportunities for composites: (1) Automotive, (2) Infrastructure and (3) Aerospace, as shown in Figure 1. **Automotive:** Growth will require widespread implementation of automation to meet the high-volume, low-cost requirements of this industry, and this increased use of automation will drive the increased use of modeling of composite manufacturing processes to assist in the design and tuning of these automated processes. The lack of a large supply of low-cost carbon fiber is one of the major barriers to realizing the maximum benefit of weight reductions. Weight reductions on the order of 40% over today's metal-structure vehicles are possible through the combination of composites and the resulting weight drop of the automobile mechanical systems. For example, reduced-weight bodies-in-white and doors will require reduced-weight drive trains and door-lift mechanisms, respectively. Automation and cycle-time production less than two minutes will require research and development into new quick-curing resins and forming processes. **Infrastructure:** Similar to the large turbine blades in the wind energy sector, composites in infrastructure require the materials to come at a low cost per unit weight and exhibit a long service life. The size and scale of these composite structures, such as bridges and buildings, require resins with cure times that allow time for fully wetting the part, which is in contrast to the fast cure needed by the auto industry. **Aerospace:** Aerospace has been a leader in the application, processing and advancement of composite materials. This very high penetration of the use of composites is anticipated to continue. The military and commercial aerospace sectors will continue to raise the bar for the performance and to expand the number of applications of composites. The high-cost applications of these materials help to push the envelope in performance and innovation for new processes, which will enable composite technologies to migrate to the sectors that are constrained by low-cost requirements. While the marine, wind, and sports and recreation sectors can continue to grow, it is not anticipated that the growth in each of these sectors will be as significant as the top three. However, all sectors should benefit from the advancements in materials, processing, automation, modeling and workforce development that will be led by the auto, infrastructure and aerospace sectors.

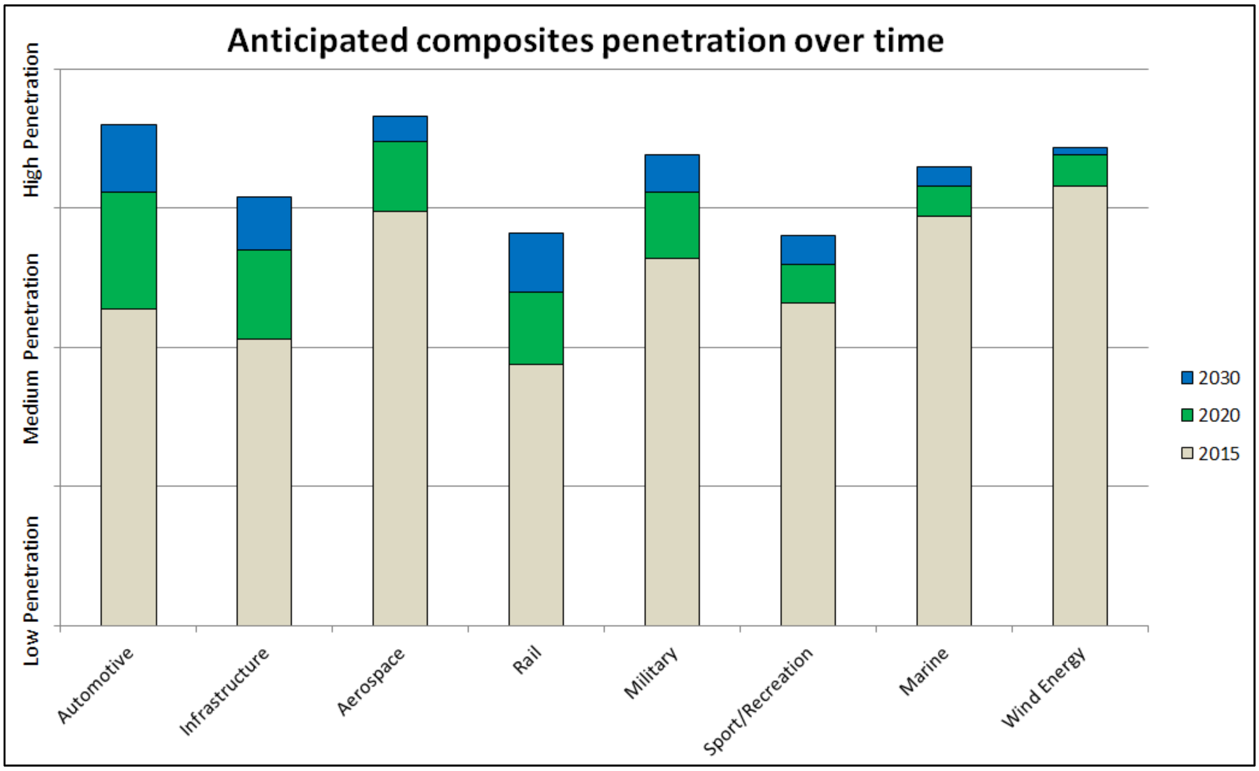

Figure 1 – Anticipated penetration of composites by industry sector (2014 survey)

Overall, the grand challenges identified for the growth of the composites manufacturing industry are the development of a sufficiently skilled workforce (Grand Challenge #1), reduction of cycle time for part production (Grand Challenge #2), expansion of knowledge and tools enabling manufacturers and designers to use new processing methods and materials (Grand Challenge #3), and advancement of the material performance (Grand Challenge #4). This report documents the drivers, state-of-the-art, challenges and plans for addressing those challenges though four primary topical areas: (1) Advancing processing methods, (2) Future of materials, (3) Innovations in predictive modeling tools, and (4) Workforce development. There are many intersections between these topics. Appendix B summarizes the drivers, barriers, action items that are associated with advancing the state of composite processing in the U.S.

2. GRAND CHALLENGES

Grand Challenge #1 (GC-1) – Development of a Sufficiently Skilled Workforce

The most significant barrier to growth of the U.S. composites manufacturing industry is the availability of a well-trained and sufficiently-sized workforce,. Challenges exist in retaining the current workforce and in training of workers to meet the present demand for employees. The U.S. Composites Manufacturing Industry requires skilled workers at all levels of education from entry-level skilled laborers to doctoral-degree researchers. As the industry expands, the workforce needs will continue to grow and as automation increases the required workforce skills will alter accordingly.

Grand Challenge #2 (GC-2) – Reduction of Cycle Time

The most significant and wide-reaching technical challenge is enabling technologies that will facilitate the cycle-time reductions needed for low-cost high-volume manufacturing of composites. Across the different industry sectors, the cycle time can vary from minutes to days. Compared with more traditional materials, such as steel and aluminum, the processing of composites is typically longer. Very fast cycle times (1-2 parts per minute) are needed to push composites deeper into the automotive industry while cycle times of under 24 hours are desired for wind turbine blades to make efficient use of labor and factory floor space. Faster per part production will make composites significantly more competitive and desirable for a wide range of new markets.

Grand Challenge #3 (GC-3) – Expansion of Knowledge and Tools

There is a need for expansion of the modeling tools that enable manufacturers and designers to explore new processing methods and materials in a virtual environment. Many designers, engineers, and manufacturers do not currently have comfort in developing products using composites because of limits in their knowledge of the materials. Additionally, there are many limitations to and awareness of the tools for predicting the processing and performance of the materials. The full opportunity and growth of composites will not be reached without the expansion of the knowledge and the development and implementation of these tools.

Grand Challenge #4 (GC-4) – Advancement of the Material Performance

Composites are highly beneficial because of the many benefits that can be realized as a result of their mechanical behavior. Composites offer the ability for lightweighting, multi-functionality, creativity of design, innovative solutions, etc. The continued advancement of the performance of composite materials for all of these benefits will enable the growth of the use of composites, and therefore, the growth of the composites manufacturing industry.

Within this report, the outcomes of the roadmap will refer back to each of these four grand challenges (i.e. GC-1, GC-2, GC-3 and/or GC-4).

3. ADVANCED PROCESSING METHODS

The high specific-strength and high specific-stiffness properties of composite materials have long been attractive to many markets. However, the relatively high cost of composite structures due to the labor-intensive, time-consuming processing methods (GC-2) used to make them has been a barrier to widespread use. Defense applications can justify the time and cost, so military applications have widely implemented composites into designs. The wind industry uses composite materials for large wind blades because composites offer a better combination of strength, stiffness and weight than can be achieved with aluminum – not necessarily because the current blade manufacturing processes are attractive.

Currently, raw material conversion and polymer matrix composite processing consists of manual and automated methods with varying levels of process monitoring and control. Processes for shaping and curing both engineered (short-fiber) and advanced (long- or continuous-fiber) parts can be divided into two main categories: open- and closed-molding processes (hand/wet layup for thermosets, spray-up, filament winding and automated fiber placement and tape layup (AFP/ATL) and closed-molding processes (vacuum bagging, liquid composite molding (LCM), compression molding), pultrusion/continuous lamination, extrusion, structural/reinforced resin infusion modeling (SRIM/RRIM), injection molding, thermoforming, autoclave and out-of-autoclave (OoA) molding. During company visits, the FIBERS team discovered that current manufacturing trends include increased use of liquid composite molding, out-of-autoclave molding, flexible and hard automation, and thermoplastic materials.

A major opportunity/challenge for the industry is to develop new and innovative manufacturing processes. Understanding the physics associated with a processing method is paramount to developing the innovations that can lead to reduced costs and increased throughput rates, and thereby provide a pathway for the U.S. to be a leader in composites manufacturing. (GC-3) Advances in composite manufacturing, nondestructive evaluation, bonding and repair, and recycling are crucial for the successful and accelerated adoption of composites beyond high-end aerospace markets and for the expanded use of composites in wind.

The FIBERS team conducted industry surveys of composites manufacturing companies in 2014 and 2015. Responses to those two surveys highlighted new and improved composite processing methods as a priority for success. In the 2014 survey, two of the six most important challenges identified were reducing variability in processing and new-process development. Likewise, a vast majority of respondents in 2015 indicated that new processes are required for growth.

With widespread adoption of composites, the need for faster, cheaper and more robust processing methods become critical for high-volume, low-cost production scenarios. (GC-2) Cost and sustainability concerns are driving manufacturers to reduce the amount of raw materials, waste, energy and consumables associated with processing. Recycling technologies, including pyrolysis and solvolysis, are being developed to reclaim expensive fibers from scrap and end-of-life parts. Raw materials (e.g. fiber, resin and core) are currently expensive, have highly variable processing requirements and can exhibit final performance properties that are highly dependent on the processing conditions. Industry companies and the U.S. government recognize the need for rapid, low-cost carbon-fiber production, which was identified as one of the most important action items in the 2015 survey. Two-thirds of respondents to the same survey cited the need for new resins to reduce processing time and lower per-part cost. Figure 2 shows the relative significance that new resins could impact a range of industry challenges, and Figure 3 shows the relative rank of the highest priority actions for reducing the cost of materials.

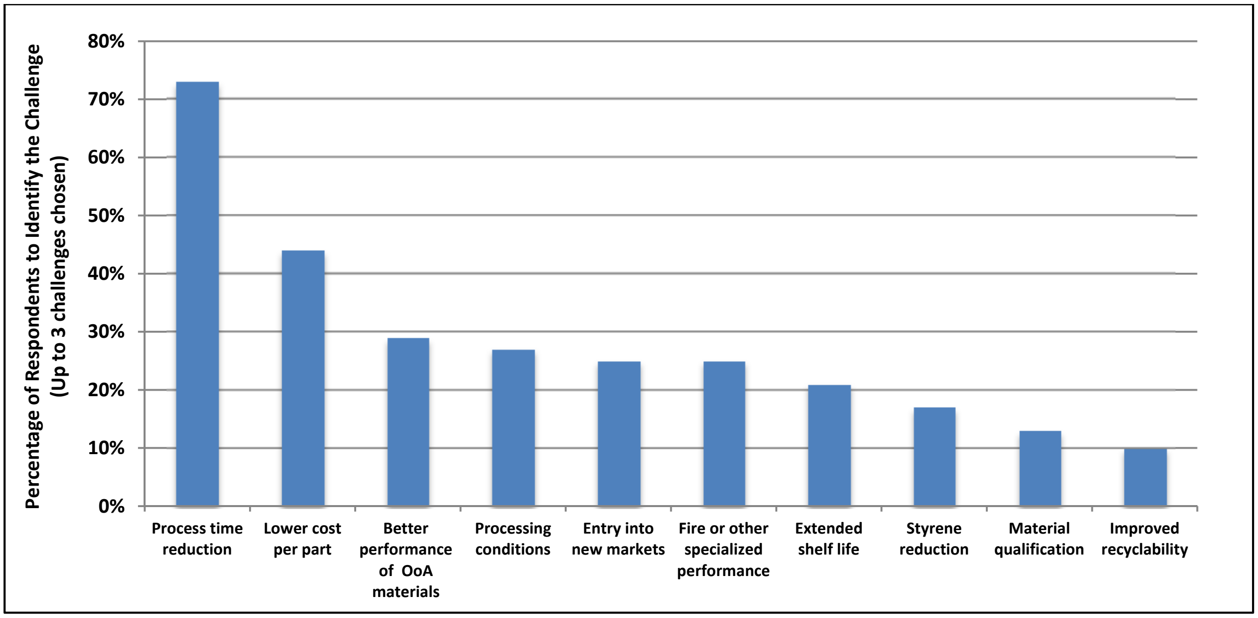

Figure 2 – Challenges that could be overcome with the use of new composite resins (2015 survey)

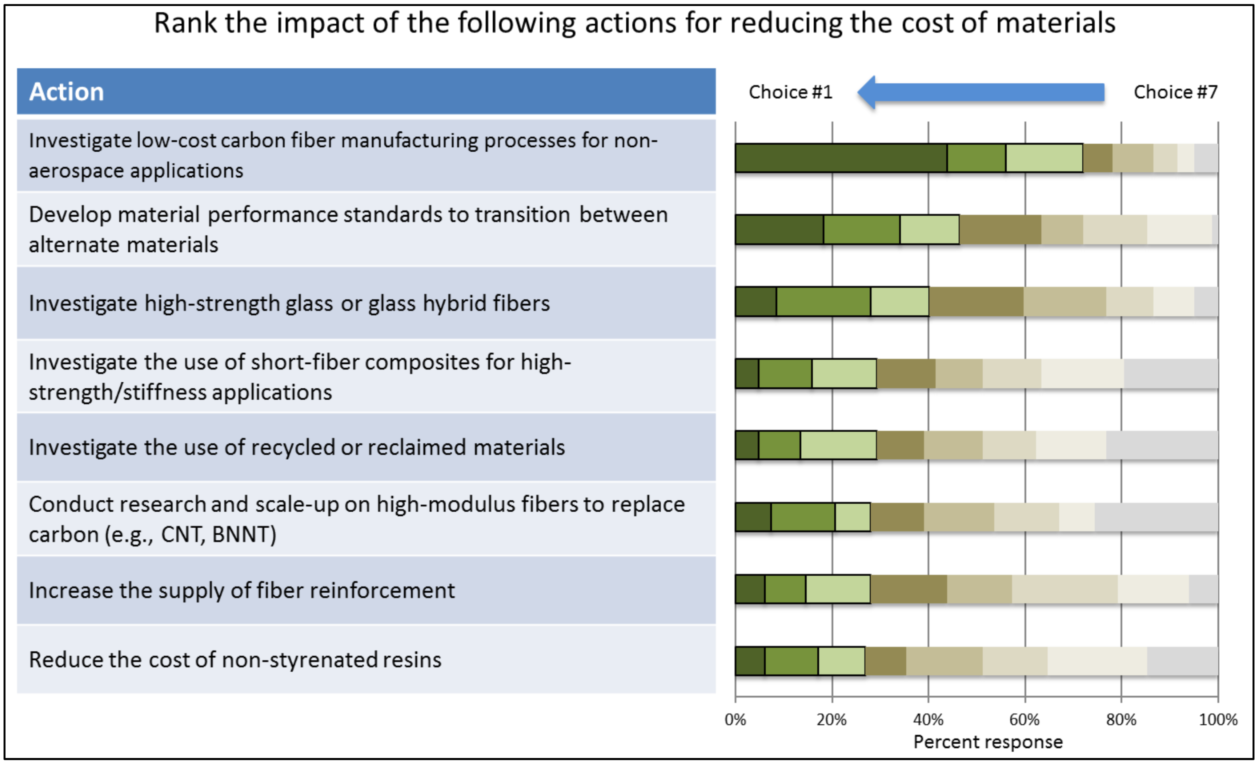

Figure 3 – Ranking of impact of the specific actions on reducing the cost of materials (2015 survey)

The needs for shorter process-cycle times (GC-2) and lower labor costs are driving the composites manufacturing industry to explore for opportunities where automation can be integrated into its processes. As a result, the incorporation of automation is expected to grow in all composite manufacturing sectors over the next 15 years with the highest increases in penetration in the automotive and aerospace sectors, as shown in Figure 4.

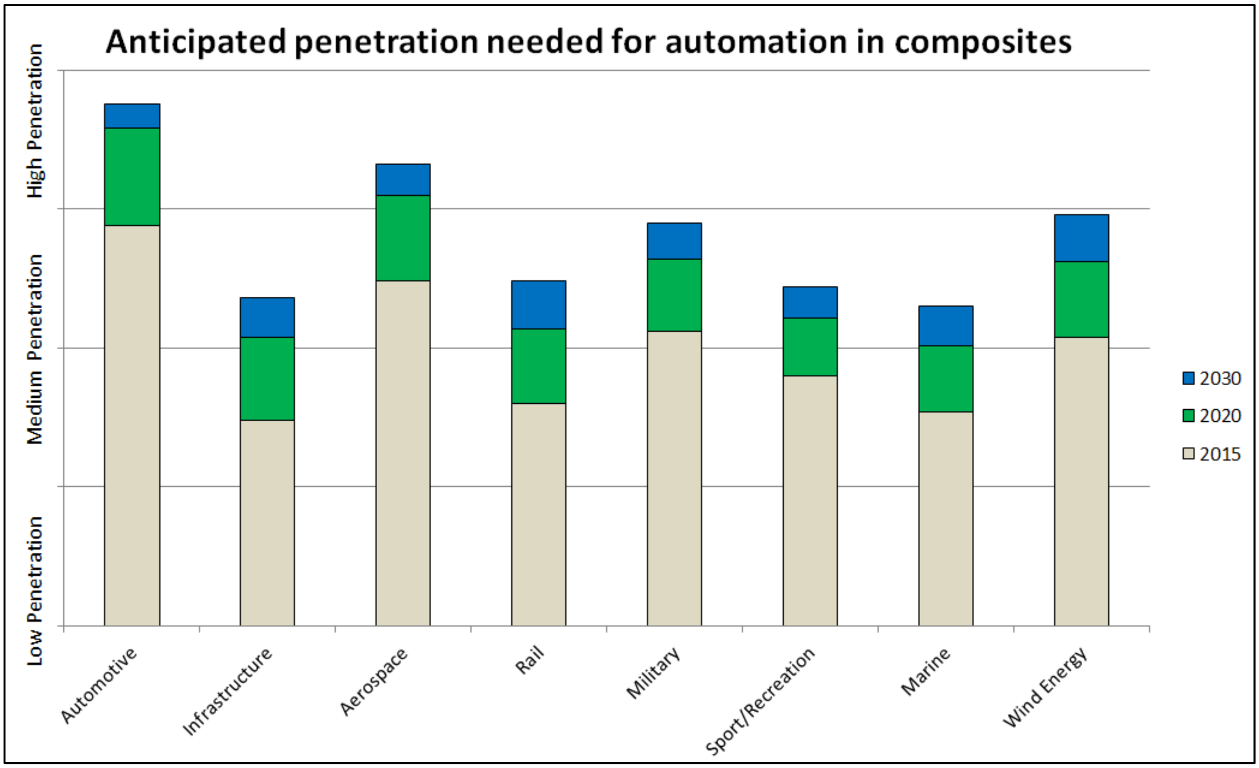

Figure 4 – Level of penetration needed in automation (2014 survey)

Despite increased market demand and opportunities for advanced composites, significant challenges exist in the U.S. for replacing traditional engineering metal alloys with composites. Figure 5 shows the ranking of the primary challenges that development of new composites manufacturing processes would overcome. The following four primary challenges were identified in the 2015 survey in order of importance to the composites manufacturing industry:

1. Reducing cycle time (GC-2)
2. Reducing material/part variability (GC-4)
3. Mitigating waste
4. Expanding the workforce that is trained in the design of composite structures and the design of the associated manufacturing processes for those structures—especially for complex part geometries (GC-1&3)

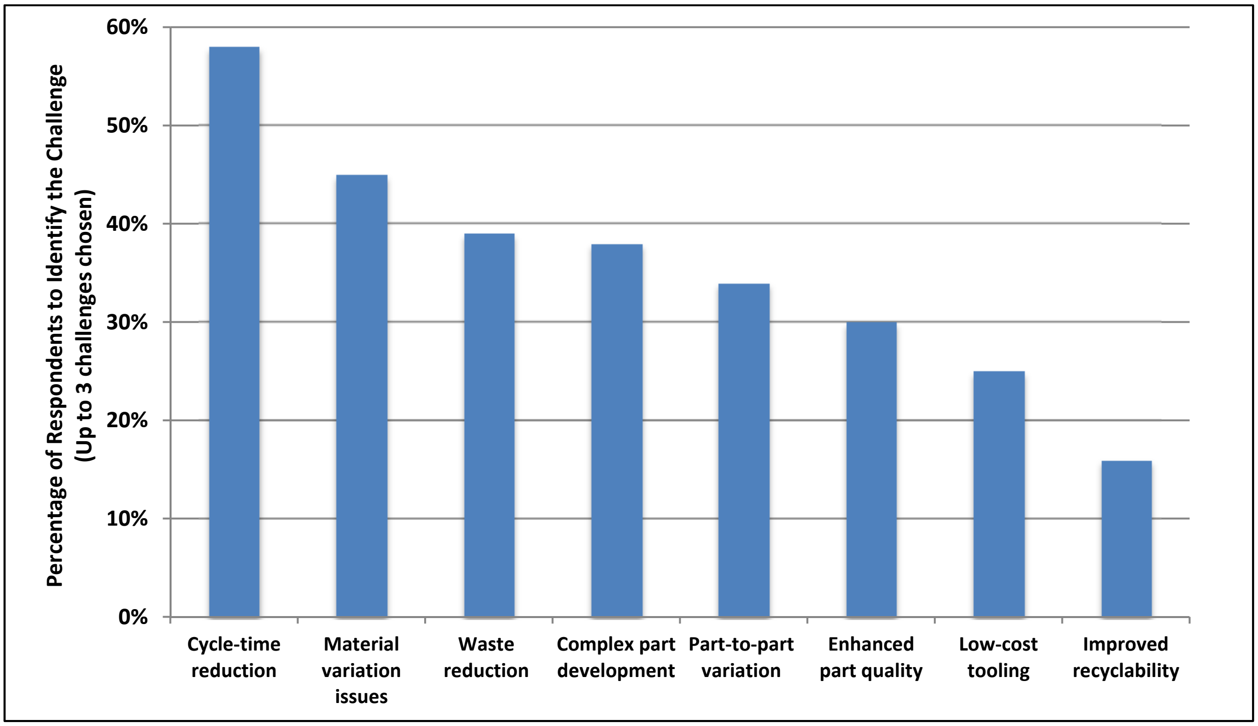

Figure 5 – Primary challenges that development of new composites manufacturing processes would overcome (2015 survey)

Reducing material and part variability was among the primary challenges identified, and the 2015 survey provided a ranking of the impact of actions on reducing process variability. Those actions are ordered in Figure 6. The workshops also identified that nondestructive evaluation methods, including ultrasonic imaging and acoustic emissions need to be widely used as a means of quality control during manufacturing.

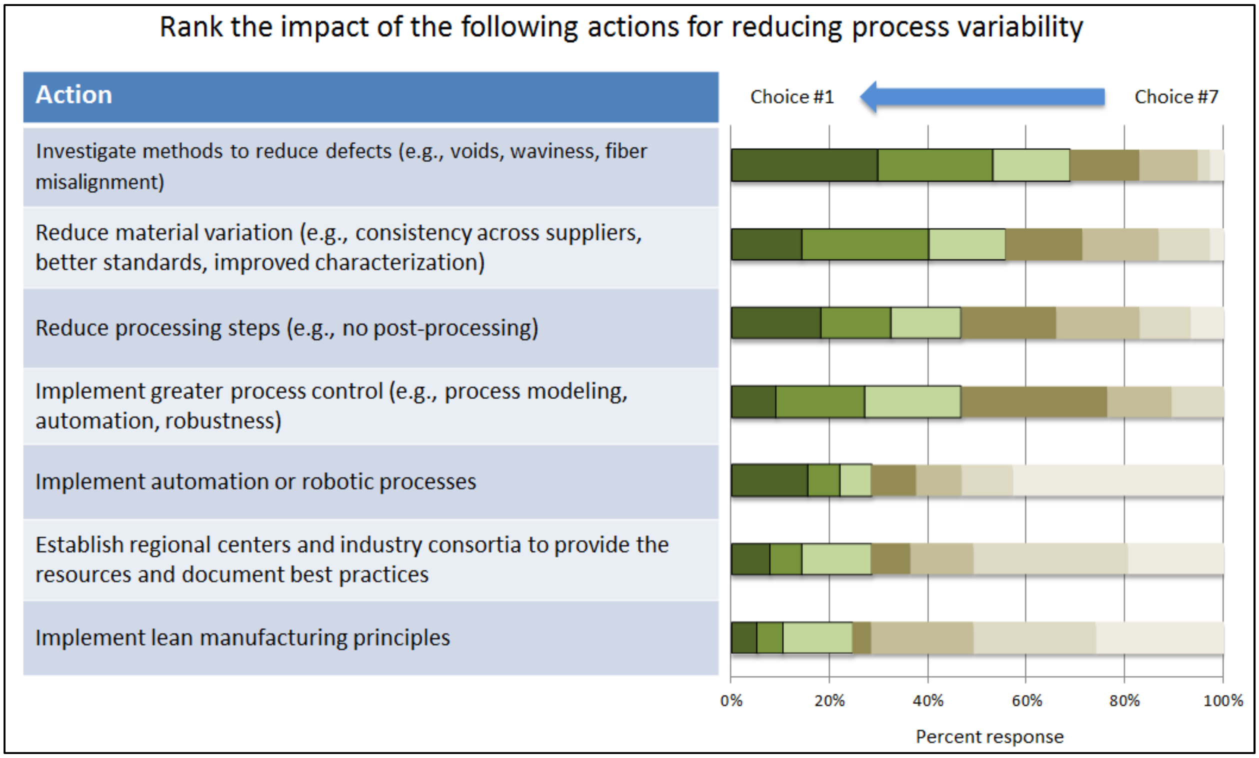

Figure 6 – Ranking of the impact of the specific actions for reducing variability (2015 survey)

A common concern by many of the SMEs that were visited by the FIBERS team was that capital equipment, engineering, energy and material costs are too high. (GC-3) Unlike some industries that recognize the benefits of research collaboration, such as the semiconductor industry, fears about intellectual property protection are making an environment where companies are duplicating research and development efforts or use outdated processes and approaches due to the lack of resources to innovate. Smaller firms are also faced with limited to no access to new equipment and state-of-the-art analysis capabilities, thereby limiting their ability to explore new processes and to justify the cost of new-process adoption.

Research investments devoted to cost reduction reduced part-to-part variability and increased productivity are priorities for the development of new processing methods. Industry, academia, government agencies and non-profit associations, such as ACMA, need to collaborate on the following:

- Development of low-cost carbon fiber manufacturing processes to facilitate the growth of non-aerospace applications. (GC-4)
- Development and implementation of robust predictive modeling, non-destructive evaluation and smart automation capabilities. (GC-3)
- Development of methods to mitigate or eliminate part defects, followed by increased implementation of process control and reduction of incoming raw material variation from the supply chain. (GC-4)

- Demonstration of technologies necessary in automation and robotics, process sensing, monitoring and control, and process simulation. (GC-2&4)
- Adoption of lean manufacturing principles.

The federal government should:

- Increase funding to train both engineers and technicians in composites manufacturing. (GC-1)
- Provide long-term support for R&D activities to assist the U.S. composites manufacturing industry to be on par and to overtake foreign competitors – especially in the European Union, where government support for composites is very high. (GC-1-4)
- Share Department of Defense knowledge in automation of composites manufacturing with U.S. industry. (GC-3)
- Set up regional technology centers with process and simulation capabilities and technical support services for use by SMEs. (GC-3)

Without significant movement on these items, many industry applications will struggle to adopt composites into their design. Collaboration among industry, academia, government, and non-profit associations are critical for successful development and implementation of game-changing processes in the U.S. composites industry. Appendix C includes a listing of potential demonstration projects and initiatives identified to help address the industry challenges through collaboration.

4. THE FUTURE OF MATERIALS

The ideal composite material systems are those that are cost-competitive with traditional materials (e.g. steel and aluminum), enable rapid cycle times, provide consistent processing results and in-service performance, and are sustainable. (GC-2) Concerted research and development efforts have begun to meet these requirements. Sustained progress will be enabled by high-profile efforts in new carbon and glass fibers and expanded use of thermoplastics, but also by lower-visibility investments in material standards and new approaches to materials qualification.

Composite material systems are rapidly evolving to increase the performance of existing systems – notably higher strength carbon and glass fibers (GC-4) – as well as to develop new material systems, such as resins that can function in high-temperature environments. Innovation in material formats is co-evolving with the increased utilization of automation and out-of-autoclave (OoA) processes (GC-2).

Automation requires materials with tight tolerances and low variability to produce parts with minimal intervention during the manufacturing process and thereby realize the full promise of in-service performance benefits. OoA processing is gaining traction in numerous industries due to dramatic reductions in void volume fractions that approach those of parts processed by autoclave. Thermoplastic composites are increasingly deployed for potential decreased cycle times and increased recyclability.

The choice of materials used in composites manufacturing is primarily driven by industry requirements and government investments and regulations. Industrial requirements for materials focus foremost on cost reductions enabled by lowered raw materials costs, as well as attractive processing parameters, such as short cycle times, low processing temperatures and zero scrap rates. Government investments in composites manufacturing should aim to increase sustainability via recycling efforts and bio-derived material sourcing and to substantially reduce the embodied energy.

Domestic government regulations are currently directed at limiting styrene and other organic vapor emissions. The FIBERS team anticipates that manufacturers will eventually be responsible for the costs associated with the end-of-life solutions for many of their composite parts. Such a responsibility provides the incentive to develop and to use sustainable material formulations that accommodate recycling (or remaking) – as opposed to sending to landfills.

Materials challenges for today's composites industry revolve around cost, cycle time, processing bottlenecks, standardization, reduced variability, sustainability and protection of corporate intellectual property and trade secrets. Figure 7 shows the 2014 survey results identifying ten composites manufacturing challenges that could be overcome by the development of new resins and the relative impact that new resins could address to each of these challenges per the results of the 2014 survey. The cost of materials, particularly carbon fiber and epoxy resins, are prohibitively high for widespread use in market segments such as wind power and automotive. Processing cycle times are a consequence of resin viscosities that define fill time, the length of time required to reach and hold cure temperatures, and lot variability. (GC-2)

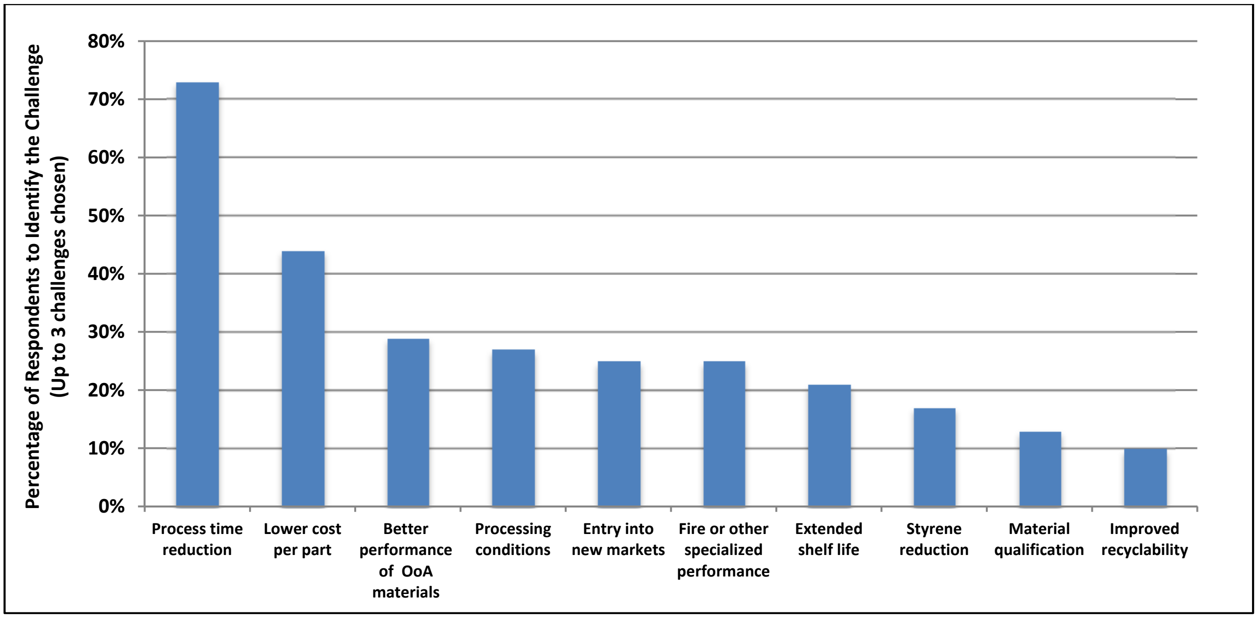

Figure 7 – Challenges to be overcome by new resin development (2015 survey)

Lot variability forces users to always bias to the most extreme condition – to design for the worst-case scenario which errs on the side of a long cure time. These issues invite negative comparisons when referenced to steel or aluminum within the automotive industry. The integration of feedback control can help reduce the negatives of lot variability.

The development of new resin materials was prioritized by two-thirds of survey respondents, with the primary aim to reduce process time and decrease part cost. These new materials, however, often require costly certifications of both material systems and processes that are a barrier to even large industry members. While industrial participants expressed conceptual interest in material recyclability and sustainable practices, few economic options are presently available. Therefore, many companies cannot make a business case for significant investment.

The FIBERS team identified actions in three domains that build on industry strengths and overcome barriers: reduction of materials costs, reduction of materials variability and development of new resins. The 2015 survey ranked the impact of actions for these three topics and those results are shown in Figures 8, 9 and 10. Three-fourths of respondents prioritize alternatives to current carbon-fiber manufacturing techniques to lower its cost for new market segments, while 40% of respondents are proponents of a similar effort for glass fibers. $_{\text{(GC-4)}}$ Half of those surveyed advocate for designing material performance standards that enable the transition between alternate materials that are functionally equivalent. $_{\text{(GC-3)}}$ Material variability must be distinguished from processing variability. Prioritized actions for material variability include increasing consistency of material inputs and formats, as well as development of materials that facilitate defect reduction in composites, as shown in Figure 9. $_{\text{(GC-4)}}$ Half of those surveyed advocate for designing material performance standards that enable the transition between functionally-equivalent alternate materials, as shown in Figure 10. $_{\text{(GC-3)}}$ Concerning the development of new resins, Figure 10 shows two-thirds of the respondents desire acceptance criteria specific to the composites industry, and a majority endorse the development of new and improvement of existing standards for composites component materials and for criteria specific to certain industry segments. $_{\text{(GC-3)}}$ More efficient and less expensive approaches to qualify composite materials, such as experimentation informed by modeling, should be pursued. $_{\text{(GC-3)}}$ Finally, though respondents did not prioritize recycling or other life-cycle materials issues, the issue was consistently raised as a looming concern among workshop participants, so research into new materials addressing environmental concerns should be pursued.

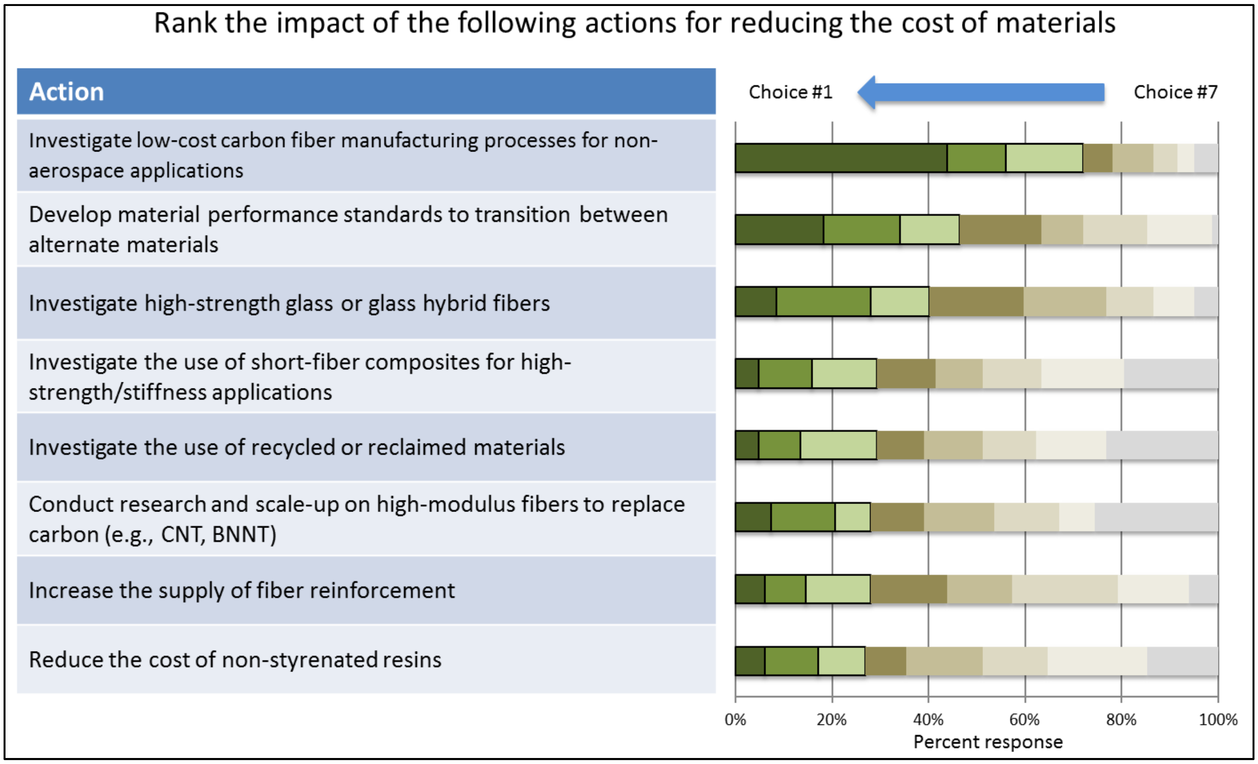

Figure 8 – Ranking of impact of the specific actions on reducing the cost of materials (2015 survey)

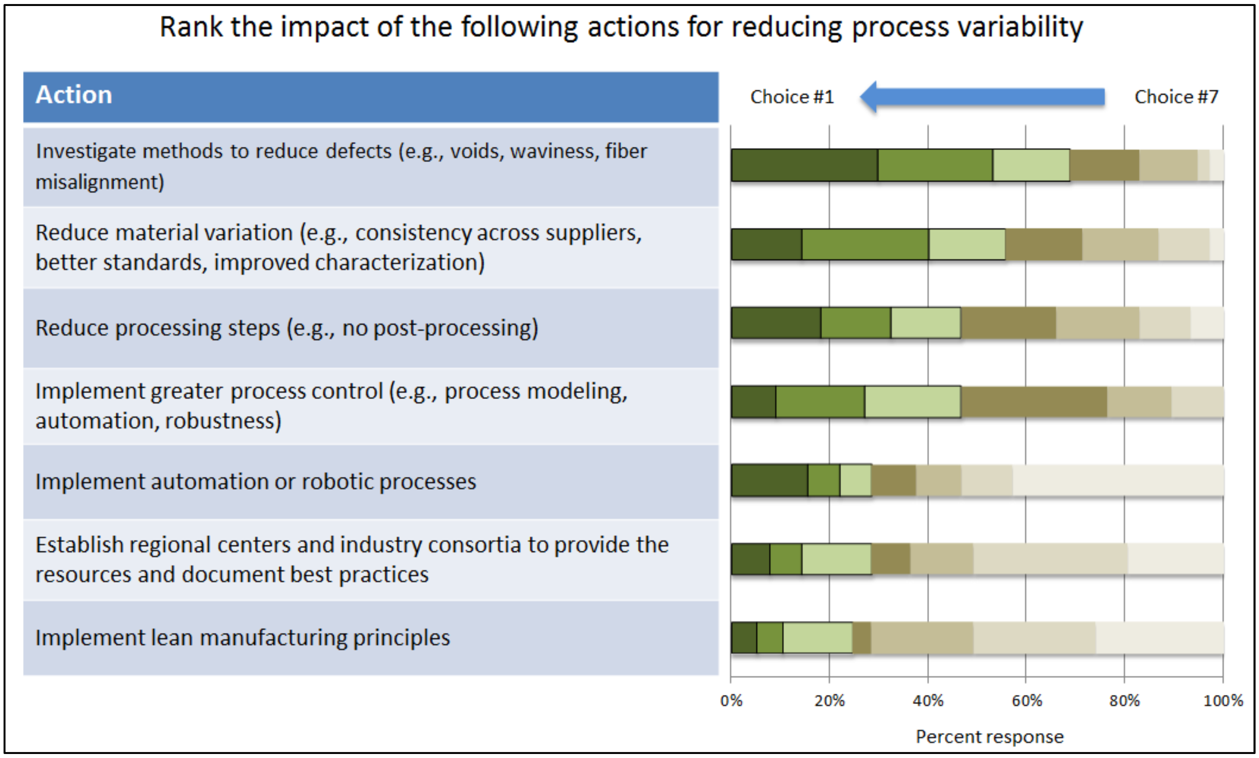

Figure 9 – Ranking of impact of the specific actions for reducing variability (2015 survey)

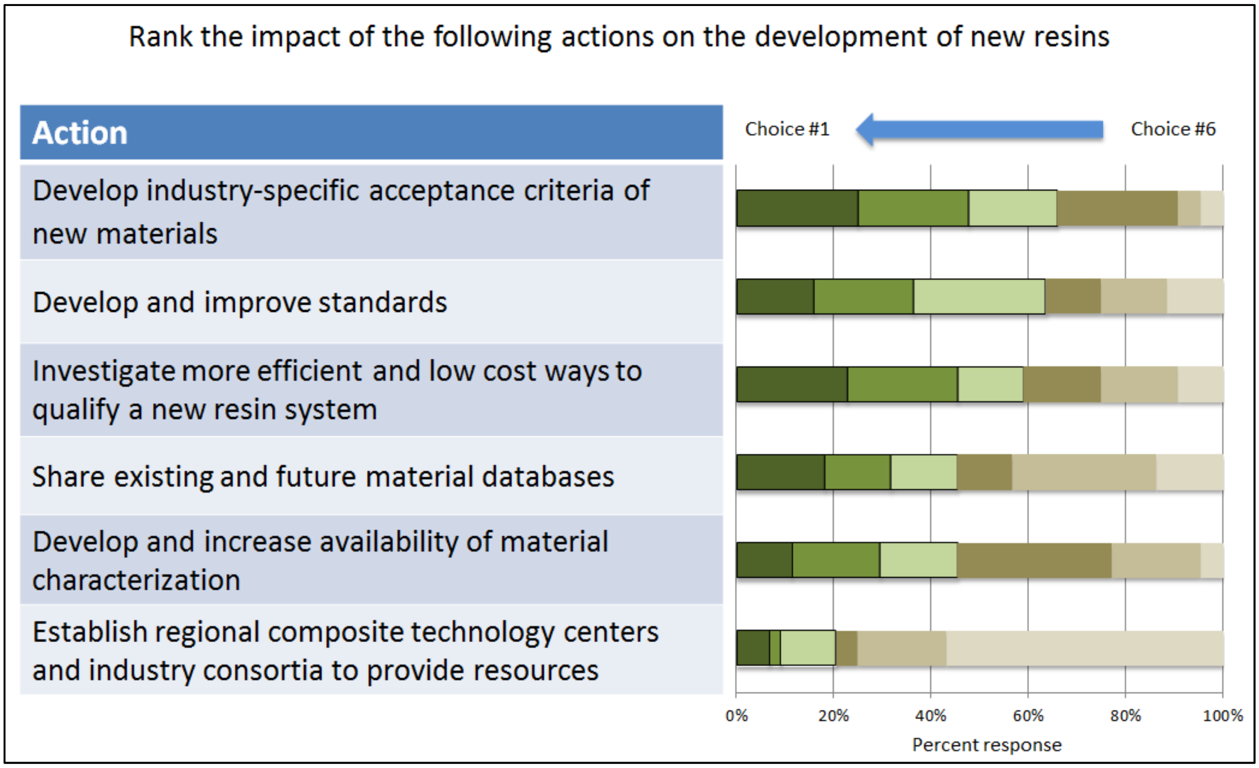

Figure 10 – Ranking of impact of the specific actions on the development of new resins (2015 survey)

5. INNOVATIONS IN PREDICTIVE MODELING TOOLS

Currently, the predictive modeling tools for composites fall into three categories: structural analysis, manufacturing process simulation and life-cycle analysis. The structural modeling tools for predicting part stiffnesses and completing stress analyses are relatively mature, while the process simulation tools are still on a growth path. These modeling tools are a valuable resource for investigating new composite designs and new processing methods. These tools provide manufacturers a virtual environment to redesign existing processes or add new processes that can facilitate improvements in the manufacturing process. Unfortunately, these tools are often underutilized, especially by SMEs, for such reasons as limited access to the tools, lack of qualified personnel with experience in using the tools, or lack of awareness that the tools even exist. (GC-3) By linking the modeling of the manufacturing process to the models of in-service performance, manufacturers could use a virtual manufacturing environment to examine the benefits and consequences of such changes as material choices, processing conditions and capital equipment options before going down the long and expensive path of product and process development.

The 2014 survey identified the anticipated penetration of modeling needed for eight different sectors of the composites manufacturing industry. The results, shown in Figure 11, indicate that aerospace currently has the highest penetration of the use of modeling. Automotive, military and wind energy are also using modeling, but show significant need for higher penetration in the coming years.

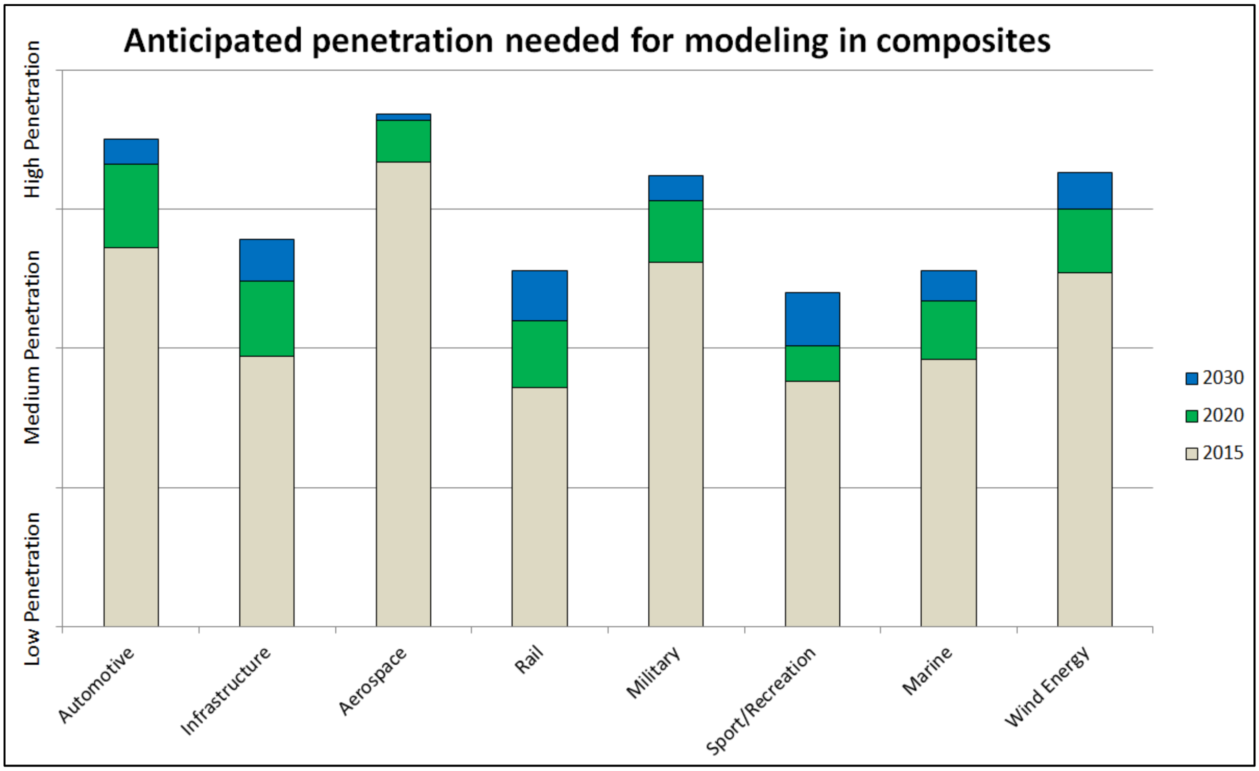

Figure 11 – Level of penetration needed in modeling (2014 survey)

The modeling tools for process simulation, predicting in-service fatigue life and life-cycle inventory (LCI) are still emerging. LCI refers to examining the environmental impact of a composite product, and an LCI model can be used to quantify the energy use and material efficiency. Currently, life-cycle studies of composites lack the granularity needed to include major constituents found in thermosets and thermoplastics. As a result, these tools cannot be easily used by designers and developers of composite products. In addition, use of these tools is limited because only a small fraction of the constituent materials has been characterized to provide the needed inputs to these models, and many of those characterizations are incomplete.

The objective to decrease product development costs while improving performance compared to existing composite and metal products is the driving need for development of improved predictive tools and for increasing their use across the industry. Improved predictive simulations can reduce the current practice of overdesigned parts, thus reducing material usage – both waste and the amount of material in the product life-cycle. Stakeholder expectations for environmental improvement of composites, recycling and a link between greater life-cycle and lower total product costs also need to be addressed by industry. Indirect drivers for the use of LCI models include international expectations for environmental product declarations, government policies on purchases and financial institutions' perception of the benefit of clear environmental profiles.

The widespread adoption of predictive modeling tools faces challenges that include the lack of material data inputs and of a general recognition of the advantages that can be gained from such modeling. Currently, processes rely heavily upon in-house experience and the design-build-test process. The reliance on past experience limits the vision of possibilities for process and part design to what is known from past history. Virtual models can expand the range of possibilities to be considered. Also, industry is generally unable to demonstrate and communicate the environmental benefits of new composite products. Both process simulation and LCI tools are hampered by a universal concern over the lack of availability of a standardized material database. Cost and access to training in the proper use of some of the tools is also a concern.

The implementation of demonstration projects and initiatives, which include the use of predictive modeling tools, can educate industry about the capabilities of these tools and show their value in expediting the design of manufacturing processes. Such demonstration projects and initiatives are currently being pursued through IACMI. Additionally, it is important to expand materials databases to include the properties needed by these simulations. Ideally, a central clearinghouse for the data should be freely available: a collaboration of federal agencies, such as the Department of Energy, the Department of Defense, the Department of Commerce, NASA, the Federal Highway Administration and/or IACMI would be the obvious groups to underwrite such an initiative. $_{\text{(GC-3)}}$ A list of potential Demonstration Projects is provided is Appendix C.

Life-cycle predictive tools also need further development. The availability of representative, non-proprietary composite life-cycle inventory data for the largest composite end-use product groups is needed. Data are required for the majority of chemical constituents and composite assembly techniques. It is critical to develop life-cycle profiles of composite recycling and benefits in recycled or repurposed composite materials.

6. DEVELOPING A SKILLED WORKFORCE

Workforce development is a human resource strategy that holistically considers workers, barriers that workers face to entry into the workforce and challenges for companies to retain these workers. The composites workforce resides along a spectrum from no composites-specific training to engineers with doctoral degrees. Figure 12 is a schematic showing the educational process for the composites industry workforce. Graduates with composites knowledge tend to be hired before graduation. However, the alignment of education and training programs with industrial requirements is variable and results in mismatches between worker skillsets and manufacturer needs.

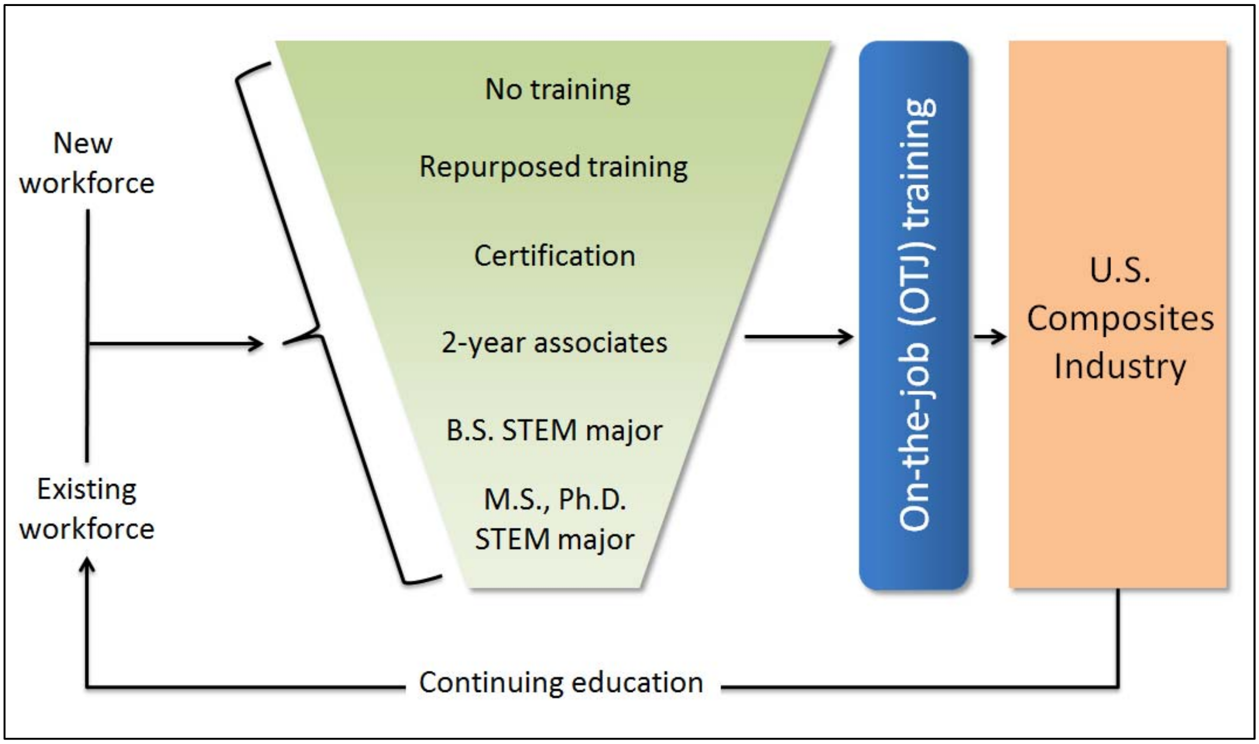

Figure 12 – The diverse training landscape for the domestic composites industry workforce

Currently, high school graduates enter the workforce or college unaware of composites manufacturing as a career. Education and training programs may not be tailored to match regional industry requirements, despite a significant fraction of workers remaining geographically local to their respective educational institution. No national standards or accreditation body exists for the industry, which hinders consistent education standards and transfer of skills between composites companies. Efforts must be pursued to inform K-12 students about the roles of composites in society, e.g. high-performance cars and architecture, and career opportunities.

The manual, complex and craftsman nature of composites manufacturing impedes the influx of employees from other manufacturing sectors. Many design engineers are unfamiliar and uncomfortable with the design flexibilities associated with composites, and this restricts the broad adoption of composites. Until there is a significant population of engineers with knowledge on how to design composite parts and who understand the processes used to make such parts, growth in the number of composites applications will continue to be slow. (GC-3)

There is a high turnover of employees across all composite manufacturing sectors. Figure 13 summarizes the typical length of time an employee stays with a company. Company size correlates with length of employment; the median employment at companies with retention of less than one year is 150 employees, while companies with greater than 1000 employees have median employment tenures of 5 to 10 years. Nearly 70% of companies report a challenge in retention of their qualified workforce, while transfers to other industries exacerbate the skills shortfall within the composites sector. These transfers are driven by the physical aspects of the work environment, as well as pay differentials with other industry segments. Figure 14 summarizes the relative impact for actions that can be taken to increase employee retention in the composites manufacturing industry.

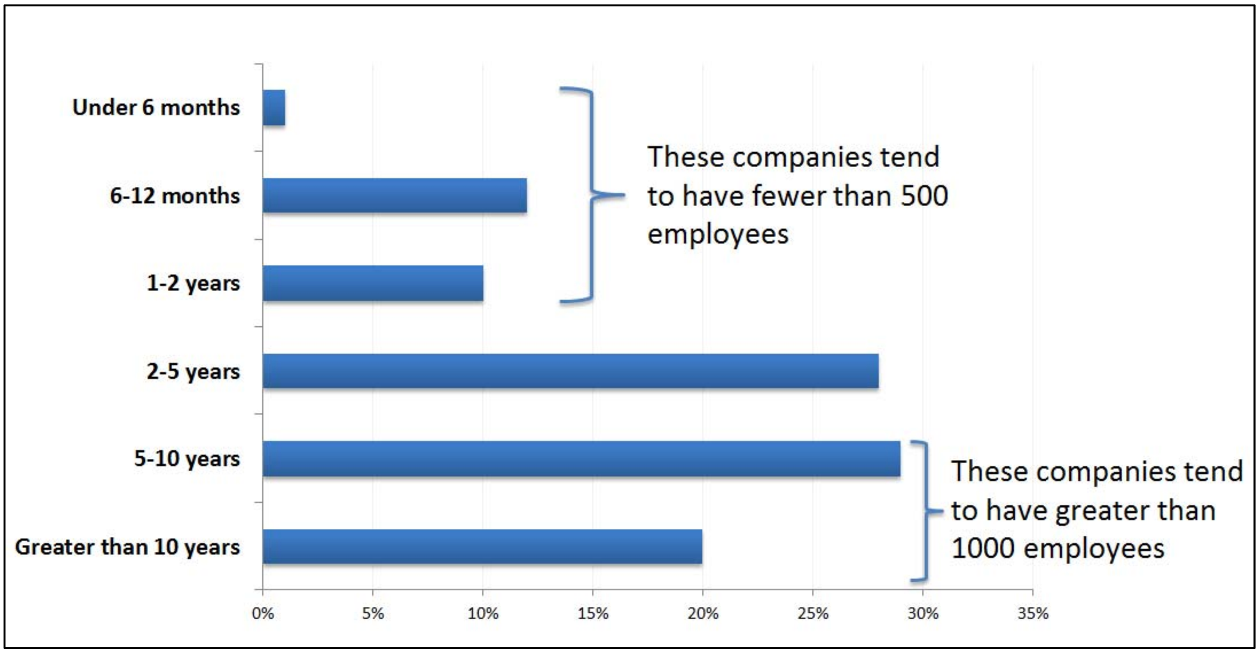

Figure 13 – The average turnover rate for hourly workers in the composites industry (2014 survey)

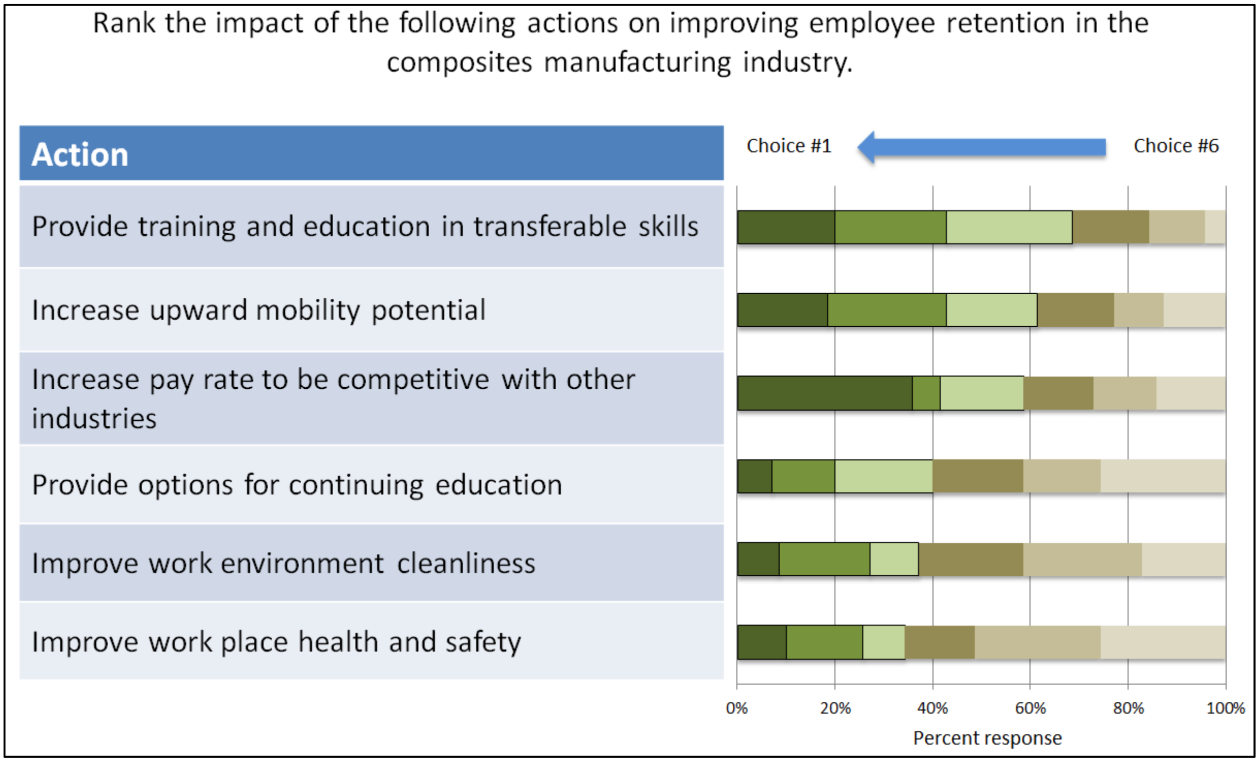

Figure 14 – Ranking of impact of specific actions on improving employee retention (2015 survey)

Continual growth of the composites industry requires skilled labor at all levels, as shown in Table 1. Almost 70% of companies report challenges in the availability of a qualified workforce. (GC-1) While expected hiring is greatest for high school graduates, a quarter of respondents expect to hire at the master's and doctoral levels.

Table 1 – Expected future recruitment of composites workforce

Highest level of educational attainment	Percent respondents hiring at the related educational level
High school	60%
Bachelors of Science (B.S.)	55%
Masters of Science (M.S.)	28%
Doctorate (Ph.D.) in STEM	23%

Improvements in recruitment, retention and workforce development require a large foundation of well-structured workforce training programs, engaged industrial/educational partnerships and educational outreach in the domestic composites industry. Figure 15 shows the impact of specific actions on the availability of a qualified regional workforce. Greater than 80% of industry respondents prioritize the generation of composites transfer pathways between high school, community colleges and universities. More than half the respondents rank high the development of co-op and internship programs focused on industry input and certification programs that prioritize industrial relevance.

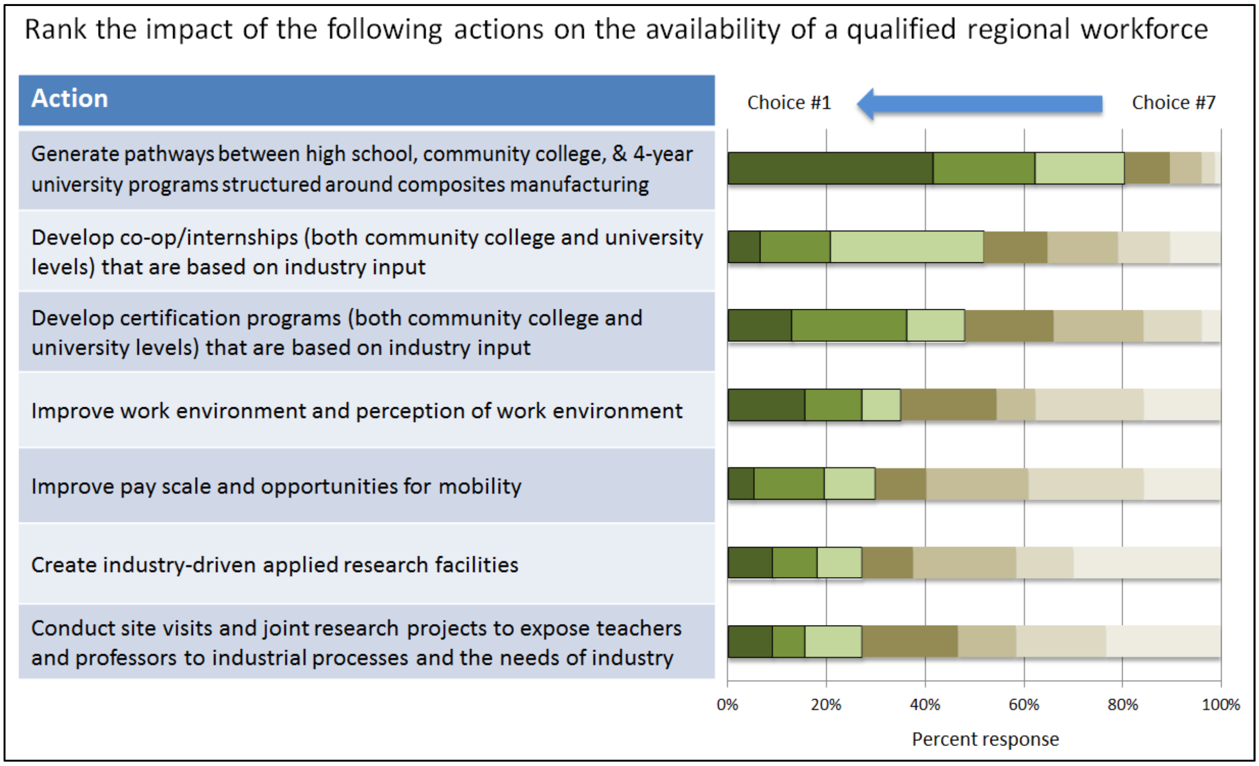

Figure 15 – Ranking of impact of specific actions on the availability of a qualified regional workforce (2015 survey)

Each partnering education institution must have personnel motivated to establish these pathways and programs, who are actively engaged with and responsive to their industrial counterparts. The academic institutions with plans to continually update content with industry input will improve the competitiveness of their alumni. Industry, likewise, should reach out to academic institutions and engage in long-term, sustained investment in strategic partnerships. Large majorities of industry respondents prioritize re-training of the existing workforce in transferable skills and the establishment of pathways for upward mobility of employees throughout their career as vital to the retention of a qualified workforce.

The future of composites manufacturing is one in which new college graduates enter the workforce with a broad, relevant and up-to-date knowledge of composites manufacturing methods and materials. (GC-1) Projects to achieve this future include development of industry-led standards for accreditation, to enhance education quality and to enable ease of transfer within the industry, creation of pathways to climb the employment ladder and development of instruction modules to increase composites' visibility and to teach a generation of design engineers how to incorporate composites. Putting these enabling projects in motion is the goal of a comprehensive workforce development plan.

7. CONCLUSIONS

The grand challenges for the growth of the composites manufacturing industry in the U.S. can be overcome by undertaking a variety of projects and initiatives. The composites industry is a very important to U.S. manufacturing. There are great opportunities, including part performance and an expanded workforce, to be gained from solving the challenges that face the industry. This roadmap identified four grand challenges and outlined the actions that must be undertaken to enable the growth of the industry.

The development of a sufficiently skilled workforce was one of the most discussed challenges. The future of composites manufacturing is one in which new college graduates enter the workforce with a broad, relevant and up-to-date knowledge of composites manufacturing methods and materials. Government should increase funding to train both engineers and technicians in composites manufacturing. Initiatives to achieve this future include development of industry-led standards for accreditation, enabling ease of transfer within the industry, creation of pathways to climb the employment ladder, development of instruction modules to increase composites' visibility and teaching a generation of design engineers how to incorporate composites. Putting these enabling projects in motion is the goal of a comprehensive workforce development plan.

The reduction of cycle time for part production was one of the specific technical challenges identified across all industry sectors. Research investments devoted to increased productivity are a high priority. Industry, academia, government agencies and non-profit associations need to collaborate on demonstrations of technologies necessary in automation and robotics, process sensing, monitoring and control, and process simulation. Processing cycle time can be a consequence of material choices, therefore projects enabling innovations in resins and material formats should parallel automation efforts. Long-term support for R&D activities is needed to assist the U.S. composites manufacturing industry to be on par with and to overtake foreign competitors, especially in the European Union where government financial support for composites is very high.

The expansion of knowledge and tools enabling manufacturers and designers to use new processing methods and materials was one of the broad technical challenges identified across all industry sectors. Research investments devoted to cost reduction and increased productivity are priorities for development of new processing methods. There is a need to collaborate on the development and implementation of robust predictive modeling, non-destructive evaluation and smart automation capabilities; share Department of Defense knowledge in composites manufacturing automation with U.S. industry; and set up regional technology centers with process and simulation capabilities and technical support services for use by SMEs. Industry advocated for (1) designing material performance standards that enable the transition between alternate materials that are functionally equivalent, (2) development of material system acceptance criteria specific to the composites industry, (3) the development of standards for composites component materials and criteria specific to certain industry segments which include experimentation informed by modeling. The implementation of demonstration projects and initiatives, which include the use of predictive modeling tools, can educate industry about the capabilities of these tools and show their value in expediting the design of manufacturing processes. Additionally, it is important to expand materials databases to include the properties needed by these simulations. Ideally, a central clearinghouse for expanded material data should be freely available.

The advancement of composites material performance was one of the broad enabling challenges identified across all industry sectors. More reliable, more predictable, and more functional composite material performance will grow the industry. A majority of industry prioritized developing alternatives to current carbon-fiber and glass-fiber manufacturing techniques to lower its cost for new market segments. Prioritized actions for material variability include increasing consistency of material inputs and formats, as well as development of materials that facilitate defect reduction in composites. There is need to collaborate (1) on the development of low-cost carbon fiber manufacturing processes to accelerate non-aerospace applications, (2) on the development of methods to mitigate or eliminate part defects, (3) on the implementation of more process control and reduction of incoming raw material variation from the supply chain, (4) on the demonstration of technologies necessary in automation and robotics, process sensing, monitoring and control, and process simulation, and (5) on providing long-term support for R&D activities to assist the U.S. composites manufacturing industry to be on par with foreign competitors.

Overall, the U.S. Composites Manufacturing industry is strong, however the roadmapping activities identified opportunities for significant increased penetration of composites across all sectors. These opportunities span the range from workforce training programs to technical innovations in manufacturing processes, materials development and modeling. Industry, academia, government and non-profits must collaborate on demonstration projects and initiatives to realize these opportunities. Collaborations such as IACMI are positioned to address some of the industry’s challenges. Industry and government must support these and further efforts to address all of the identified Grand Challenges.

8. ACKNOWLEDGEMENTS

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Appendix A – FIBERS Consortium Activities

The FIBERS Consortium conducted two national surveys and organized seven workshops around the country to generate this technical roadmap for the future of the composites manufacturing industry. Each of these activities built upon the work of the prior events and activities. The consortium also hosted regular virtual meetings to discuss and to go through the results and to coordinate activities.

Surveys

National Survey #1 – November 2014 – January 2015

National Survey #2 – October 2015 – January 2016

Workshops

Workshop #1 – Regional – Lowell, MA (August 8, 2014)

Workshop #2 – National (CAMX) – Orlando, FL (October 14, 2014)

Workshop #3 – National (ACMA) – Washington DC (January 16, 2015)

Workshop #4 – Regional (SAE) – Detroit, MI (April 20-21, 2015)

Workshop #5 – Regional (SAMPE) – Baltimore, MD (May 18, 2015)

Workshop #6 – Regional – Los Angeles, CA (January 26-27, 2016)

Workshop #7 – National – Lowell, MA (March 29-30, 2016)

Appendix B – Compiled Roadmap Activity Notes

This appendix includes a compilation of comments contributed by various participants in the roadmapping workshops, surveys and discussions. The comments provide value to the context for the discussions and responses which led to the development of the roadmap but do not necessarily express the views of the authors or a consensus of the participants.

Advancing Processing Methods

Industry drivers for composites processing methods

(with relevance to low, medium and/or high performance parts in parentheses)

Category	Specific Drivers
Process Technology	• Need for more hard and flexible automation and process monitoring/control for key manufacturing processes due to high variability in raw material and manufactured part quality, high labor costs, high scrap rates, low production rates, long design change times, lack of process traceability, and automatic data collection capability for process control (low, med, high) • Difficulty for composite manufacturers to figure out how to strategically implement process automation (low, med) • Need for processes with lower cycle times and overall cost due to high production demands by certain industries (low, med) • Need to introduce automation incrementally as justified by the economics (low, med, high) • Need for more robust processes and control systems (e.g., statistical process control) that can reduce environmental sensitivity and improve material and product quality (low, med, high) • Trend with manufacturers to make processes lean (i.e., eliminate all waste), reduce the number of steps involved, and manufacture to net shape, e.g., eliminate need to de-flash parts post curing (low, med) • Need to reduce variability in short fiber orientation and property homogeneity for compression molding, transfer molding, and injection molding of engineered composite parts (low) • Need to develop reliable and repeatable non-destructive evaluation (NDE) methods for defect identification and characterization (med, high)
Materials	• Need for rapid and low-cost carbon fiber manufacturing (low, med) • Need for faster cure resins with the same mechanical properties as long-cure resins to reduce manufacturing cycle time (low, med, high) • Need for more effective and production-friendly adhesives and processes to fit and bond composite and metal components together and reduce variability (med, high)
Cost	• Interest in rapid and low-cost tooling systems (med, high) • Need by certain industries with high production demands (e.g., automotive) for processes with lower cycle times and overall cost, e.g., pultrusion, press stamping (low, med) • Need to reduce the high cost of labor (med, high)
Standards	• Need for more reliable test methods to characterize fiber/resin adhesion (med, high)

Government Policy	• Need to translate composites automation knowledge/technology subsidized by DOD to commercial sector through policy change (high) • Need for more environmentally friendly resin systems due to OSHA law and regulation compliance for chemical storage and VOC emissions (low, med, high)
Sustainability	• Growing interest in thermoplastic composite systems and processes due to improved toughness, lower cycle times (no need to cure), and better end-of-life options (low, med) • Need to make composite manufacturing more lean by reducing the amount of raw material waste and consumables used (med, high)
Simulation/Predictability	• Need for more accurate and user friendly manufacturing processes, automation models and simulation capabilities to allow for process improvement, and justify capital and recurring expenditures on equipment and process monitoring/control (med, high)
International	• Too few U.S. composite manufacturing equipment builders per capita compared to Europe or Asia (low, med, high) • Foreign competition, especially European, is farther ahead of the U.S. in many areas of automation (low, med, high)
Education/Training	• Growing U.S. composites industry but insufficient number of engineers and technicians to support it (med, high)

Note: Items incorporated into tables have been drawn from many sources (workshops, anonymous surveys, and other professional interactions). Items are included for review and consideration but do not necessarily reflect the opinions or consensus of the editors, participants or any government, academic, industry or non-profit institution.

Common industry barriers for composites processing methods

Category	Specific Barriers
Cost	• High capital equipment costs for new process or automation, especially for low-to-medium demand products • High engineering cost and time for automation without sufficient production volume to amortize cost economically • High energy costs • High material costs for advanced thermoset and thermoplastic composites
Process Technology	• Difficulty in automating in-line part inspection and other QA/QC procedures currently performed by human workers • Difficulty in implementing automation due to generally poor part quality (tolerances, surface finish, voids, defects, microcracks) compared to metals • Extensive geometrical characterization and custom CNC machining of the precise mating surfaces required for high-performance composite and metal components bonded together • Inherent distortion of composite parts after any thermal processing
Infrastructure	• Small number of resin and fiber suppliers and corresponding limits to material options • Limited SME accessibility to new process equipment and analysis software for demonstration projects • Chemical storage and VOCs for new thermoset composites systems
Education/Training	• Shortage of engineers with R&D expertise in composite manufacturing systems and processes, automation and robotics • Shortage of technicians trained in new and conventional composites manufacturing processes
Standards	• Lack of robustness/stability in rapid production processes • Lack of manufacturing standards
Industry Adoption	• High process cycle times • Unavailability of patented or proprietary technology that could benefit the entire U.S. industry • OSHA law and regulation compliance
Design	• Need for higher accuracy parts and application of design for manufacturability principles to components/products to facilitate automation • Reduced likelihood of automation use for more complex parts or processes
Simulation/Predictability	• Lack of predictability in final-part quality made with automated processes

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Actionable tasks for processing methods to advance composites manufacturing in the U.S.

Category	Specific Tasks
Education and Training	• Encourage the federal government to provide funding for improved training of engineers in composites manufacturing process technology • Stress lean manufacturing principles throughout the composites industry to reduce raw material, consumable waste, and component variability, possibly through NIST's Manufacturing Extension Partnership (MEP) program • Create more opportunities at academic and industry conferences (e.g., ASC, CAMX, SAMPE) to compare best educational practices, hands-on activities, and curriculum related to composites materials, design, and manufacturing for technicians, engineers, and scientists
Technology Demonstration	• Facilitate engagement between the automation/robotics and composites industries to demonstrate market potential for increased use of automation among U.S. composite equipment suppliers • Document best practices with regards to implementation of automation with process sensing, monitoring, and control in the composites industry for use by SMEs • Establish more composite industry consortiums where manufacturing process/system R&D and simulation capabilities can be made accessible to SMEs and the supply base.
Government Advocacy/Infrastructure	• To achieve technological parity with foreign counterparts, encourage the federal government to increase long-term funding for industry/academic R&D and educational initiatives (all levels) focused on low-cost fiber and resin formulations, thermoplastics, automation, composites additive manufacturing (AM), NDE, and process sensing/monitoring • Encourage the DOD to share automation knowledge common in aerospace composites with the rest of the composites industry • Encourage state and federal governments to fund regional technology centers (primarily for SMEs) with R&D and process simulation capabilities
Process Improvement	• Investigate low-cost carbon fiber manufacturing processes for non-aerospace applications • Investigate reliable and repeatable NDE techniques to detect and characterize defects • Investigate sources of property variation for incoming material and process variation during conversion, manufacturing, and post processing

Note: Items incorporated into tables have been drawn from many sources (workshops, anonymous surveys, and other professional interactions). Items are included for review and consideration but do not necessarily reflect the opinions or consensus of the editors, participants or any government, academic, industry or non-profit institution.

The Future of Materials

Industry Drivers	
Materials Performance	• Reduction in material variability to decrease safety factors (in particular in surface preparation and operator sensitive process) • Achievement of higher performance via materials of higher specific stiffness • Customers' and workers' concerns over toxicity (e.g., styrene) • Development of robust modeling tools: micro-macro scale models, 3D multi-load models, multi-axis models, and multi-environment service life prediction
Cost Reduction	• Promotion of hybrid materials capable to achieve specific price points below that of high-end, non-hybrid materials • Material-driven increase in manufacturing throughput, such as faster resin cure times and formats that enable raw materials to be placed more quickly into the molds • Optimization of processing: Development of more stable resin systems for room temperature storage and BMC/SMC with unlimited shelf life**;** Decrease in maturation time for BMC/SMC
Standards & Database	• Composite Materials Handbook-17 (CMH17) • NCAMP (National Center for Advanced Materials Performance) • ISO, SAMPE • ASTM materials testing standards • SAE standards on repair and overhaul

Note: Items incorporated into tables have been drawn from many sources (workshops, anonymous surveys, and other professional interactions). Items are included for review and consideration but do not necessarily reflect the opinions or consensus of the editors, participants or any government, academic, industry or non-profit institution.

Government Drivers	
Domestic Government Policy	• Regulations on Hazardous Air Pollutants (HAP) and organic vapors driving toward reduction or elimination of styrene content in polyester resins • Sector-based regulations on recyclability requiring new solutions for recycling and reuse • CAFE fuel efficiency standards driving an increased use of light composite materials • Funding of the Institute for Advanced Composites Manufacturing Innovation (IACMI)
Sustainability	• Drive to use materials systems which are compatible with recycling and reuse • "Zero waste" processing of materials • Reduction in embodied energy through reduced energy of manufacture (e.g., lower temperature processing, shorter cycle times) and sustainable raw materials • Development of alternatives to styrene-based polyester resins
International Policy	• European Union's vehicle mandate specifying recycling percentage of materials • European Union's no-landfilling mandate

Note: Items incorporated into tables have been drawn from many sources (workshops, anonymous surveys, and other professional interactions). Items are included for review and consideration but do not necessarily reflect the opinions or consensus of the editors, participants or any government, academic, industry or non-profit institution.

Common Barriers	
Infrastructure	• Limited supply base for new, sustainable materials to market • Need for wider selection of fibers, resins, binders and fillers • Need for materials surviving extreme conditions and processing steps • Global shortage in glass supply and carbon fiber and/or their derivative products • Long lead times on pre-pegs • Fiber sizing chemistry proprietary to manufacturers
Cost	• High cost of high performance fibers (i.e., carbon) • High cost of epoxy resins (~4X that of polyester resins)
Education and Training	• Constrained pool of personnel qualified in composite materials design • Greater skill levels required than can be provided by short (e.g., 6-week) training programs with regards to materials and influence of processing parameters • Shortage of new engineers to maintain acquired knowledge in composite formulation • Limited exposure to processing of bio-based composites
Standards	• Lack of standardization of materials development and testing across the industry (in particular on pre-pegs) • High expenses of separate certification by individual companies • Scalability of coupon testing not demonstrated for long fiber composites
Manufacture/Processing	• Can be difficult to disentangle variability attributable to materials versus variability attributed to the process • Lack of low-viscosity resins (without the addition of styrene) with high glass transition temperature • Long cycle times leading to increase costs, and increase embodied energy • Automation impended by material quality and variability • Shortfalls of OoA materials • BMC and SMC formulators reluctant to introduce new materials (current equipment and infrastructure favor current resins) • Difficulties with non-linear shrinkage
Design	• Large combinatorial parameter space of materials (resins, reinforcements) difficult to quickly narrow with confidence • Unpredictable joining of materials and combinations of materials
Sustainability	• High costs and lack of performance of non-styrenated polyester resins • Substantial consumables usage, driving up cost and embodied energy • Close ties between petroleum industry feedstocks as input for resins, fibers which could constrain future growth. Bio-based feedstocks still under development • Lack of standardized recycling processes • Substantial knockdown in reclaimed fibers • Shortfalls of natural fibers: reduced strength and modulus, increased water absorption
Intellectual Property	• Companies' concern about loss of intellectual property when using centralized facilities or sharing knowledge with customers.
Simulation/Predictability	• Lack of widely accepted techniques to predict material properties with confidence (in particular during impact) • Thermomechanical and UV characterization gaps • Challenges in design-manufacturing-performance modeling

Note: Items incorporated into tables have been drawn from many sources (workshops, anonymous surveys, and other professional interactions). Items are included for review and consideration but do not necessarily reflect the opinions or consensus of the editors, participants or any government, academic, industry or non-profit institution.

Actionable Tasks to Advance Composites Manufacturing in the U.S.	
Near-Term (2015–2020)	
Standards	• Urge ASTM to upgrade standards to meet new technologies • Develop materials performance standards • Develop industry-specific acceptance criteria • Lower the cost of qualification (through modeling) • Development of a database for bond specifications • Development and/or expansion of composites performance database(s)
Research	• Develop new materials: higher-strength lower-cost fibers, low viscosity resins, specific fiber sizing, appropriate bonding and coatings • Innovate in equipment (i.e., flexible high-temperature molds) • Understand and quantify variability (for material and for process), advance knowledge in process control
Design	• Coordinate with modeling and automated design program to consider production issues and optimization; include physics and order of operation
Simulation/Predictability	• Coordinate with modeling and automated design program leaders to be able to create parts whose properties agree with measurement
Government & Non-Profit Advocacy	• Advocate through ACMA and SAMPE for transfer of technology and expertise to the commercial sector • Create a database of regional resources and facilities available for industry use
Sustainability	• Create higher performance fibers from sustainable resins • Conduct research to reduce, eliminate styrene or to capture it and recycle it
Education and Training	• Market the use of NIST MEP's at the state level as hubs of composites knowledge and skills connections • Develop training programs centered on industry identified needs, create degree-level curricula with flexible modules
Mid-Term Actions (2020–2025)	
Standards Infrastructure	• Develop material property tables with standardized properties that can be entered as supporting evidence within legal cases • Develop techniques to reduce data sets for non-aeronautical applications
Government & Non-Profit Advocacy	• Transfer of capabilities developed for U.S. defense-funded projects into the commercial sector
Education and Training	• Advertise local composites training centers and encourage these to be an integral part of the property databases
Infrastructure	• Establish a central certification hub that shares a library/database of material properties
Long-Term Actions (2026–2030+)	
Infrastructure	• Establish a series of regional facilities in which capital-intensive processing and characterization equipment is available for per use charges

Note: Items incorporated into tables have been drawn from many sources (workshops, anonymous surveys, and other professional interactions). Items are included for review and consideration but do not necessarily reflect the opinions or consensus of the editors, participants or any government, academic, industry or non-profit institution.

Innovations in Predictive Modeling Tools

Industry Drivers	
Cost Reduction	• The recognition that predictive modeling can lead to cost savings by reducing scrap and time required to produce a good part compared to a trial-and-error method of generating an appropriate process. • When compared to a trial-and-error method, robust predictive modeling tools can result in a cost savings through reduction in time required to generate a good process and reduction in amount of scrap generated. • The recognition that composite products with lower environmental impacts often represent lower-cost alternatives • Continued industrial interest in non-halogenated flame retardants for composites has led to the need to establish when these alternatives (often phosphorous-based) are less advantageous for the environment or costs. • Robust predictive modeling tools can allow for multiple part designs to be investigated before committing funds to expensive equipment or particular processes. • The cradle-to-end-of-life perspective of the environmental life-cycle analysis can be used early in RD&D to establish cost benefits • Early adopters of life-cycle tools can provide cost benefit information to product users and gain market advantage by demonstrating leadership • An accessible life-cycle database can be developed by composite manufacturers and suppliers at a low cost per company by a joint industrial effort using the latest life cycle technology developments.
Improving Part Performance	• The need by industry for accurate and user-friendly manufacturing processes and automation models and simulation capabilities to allow for process improvement and justify capital and recurring expenditures on equipment and process monitoring/control. • The desire for robust simulations that predict forming and structural behavior are driving the development and use of modeling predictive tools.
Part Weight Reduction	• CAFÉ standard for fuel efficiency are driving automotive manufacturers to reduce the weight in all parts. • Improved understanding of the relationships between design, manufacturing and part performance can help reduce the weight of the part and the material waste.
Sustainability Efforts	• The need to account for the end-of-life phase of composite products is creating an industry interest in the recycling and reuse of whole composites, of resins, or of fibers • Continued industrial interest in non-halogenated flame retardants for composites has led to the need to establish when these alternatives (often phosphorous-based) are less advantageous for the environment or costs. • A large diverse baseline of the chemicals and materials comprising composites can help predict the benefit and impact of new concepts. In this regard, life-cycle analysis is the baseline for changes that constitute the roadmap of this industry. • Society (consumers) and financial institutions (who fund new manufacturing) are expecting composite-product firms to contribute to sustainability, often as environmental improvement. Life-cycle technology used by manufacturers can demonstrate their commitment to greater sustainability.
Standards	• The use of life-cycle information can be cross-cutting to include a wide range of industrial products containing composites and thus developed in a more cost-effective manner
Design	• The availability of more material-based life-cycle inventory data can facilitate design choices that more easily add improved environmental footprint information to the complex, innovative design of new composite products. • A structured life-cycle inventory database can be viewed as another complete materials properties resource for constituents of composite products.

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Government Drivers	
Government Policy	• Increasing laws and administrative procedures, at Federal and State levels, requiring clarity in environmental footprints (such as carbon or water profiles), environmental product declarations (EPDs), demonstrated levels of reuse/recycle, and producer responsibility, all support the benefit of science-based life-cycle technology for predicting quantitative environmental benefits • Product purchase requirements that include life-cycle information also drives greater use of the tool and likely demonstrates the benefits of composites in products.
International	• The use of life-cycle concepts was first developed in the U.S. (1960s) but is now more wide-spread in Europe, and hence European markets, manufacturing organizations, and governments have greater expectations of life-cycle profiles for products such as those with composites. • The U.S. leads in the evolution of life-cycle to link life-cycle transparency and scientific basis to the engineering practices used to design and manufacture composites. • The desire to keep up with the progress observed in the European Union is driving the development and use of modeling predictive tools in the U.S.

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Common Barriers	
Infrastructure	• Life-cycle predictive tools o A mechanism to readily access current and future lci data is not in place. • Modeling predictive tools o High cost of software (especially for small companies) is a barrier to its use, but cost of wasted materials if modeling is not used can be large too. o Lack of centralized location to allow short-term or trial usage of software ▪ Cloud usage (for buffering etc.) may dissuade some entities from using shared resource. o Lack of database with universally-accepted material properties. o Segregation of IP with centralized materials database, software usage, consulting services etc.
Education and Training	• Life-cycle predictive tools o Experience at BASF, Dow, DuPont and others, is that until such predictive information are available, to improve the life-cycle environmental footprint, those in corporate and educational institutions cannot use this technology. Once available, the learning curve is easy and use becomes more widespread. • Modeling predictive tools o Workforce with appropriate experience is limited. ▪ Design, Manufacturing, Code Development etc. o Decision makers are not educated with respect to capabilities of these types of models. o Lack of budget in U.S. for developing and running mentoring and training programs. o Lack of composites programs at universities to encourage degree-level education.
Standards	• Modeling predictive tools o Lack of standardized material properties (and material properties that are often specified as a range) o Lack of knowledge of knockdown properties for recycled materials o Lack of standardized modeling processes including lack of verification and validation procedures o Lack of performance standards with respect to high-strain rates o Lack of standards should legal issues arise
Demonstration	• Modeling predictive tools o It has not yet been clearly demonstrated to smaller companies that these tools will significantly reduce the cost of materials and decrease scrap. o Often models are not accepted without test correlation o Lack of robust predictive damage models for impact and crash simulations of formed part or system (may be related to lack of material property database) o Lack of design tools for crashworthiness. o Lack of accurate/effective design tools for the engineering community that can optimize the topology for composite solutions o Inadequate design modeling. o Inadequate process modeling. o Joining and repair models are limited to the macroscale. o Void with existing simulation tools as there are no robust simulation tools linking the forming of the raw materials to the resulting response of the manufactured part under normal operating conditions or hypothetical accident conditions. o There is a need for the manufacturing science to be embedded in predictive computer simulations. o Significant challenges in design-manufacturing-performance modeling exist. o Inadequate prediction of defects. o Lack of evidence that the use of the existing predictive tools accelerates the design process. o Need for demonstration projects to address barriers.

Research	• Life-cycle predictive tools o With new life-cycle inventory methods currently available, the barrier is in demonstration (RD&D) • Modeling predictive tools o Accurate models take a long time to develop. Then, there is slow transfer of that knowledge from academic research institutions to manufacturers.
Government Advocacy	• Modeling predictive tools o It is not perceived that government advocacy is a barrier to increased development and use of modeling predictive tools. However, greater government advocacy could assist with increased development and use of these tools.
Design	• Life-cycle predictive tools o Use of life-cycle inventory data to demonstrate corporate commitments for environmental improvement can be time-consuming, but offers advantages to early adopters and in market impact. • Modeling predictive tools o Prior experience with design tools that were not user-friendly becomes a barrier to trying new design tools. o Process design becomes more valuable to a company and less likely to be shared as the company becomes more adept at making a good-quality part each time. o Cost of uncertainty due to inadequate design model. o The known need for better predictive tools to aid in the design process is a barrier to use of current design tools.
Sustainability	• Life-cycle predictive tools o Societal and market assumptions that no increase in cost is acceptable is a barrier that leads to a more narrow range of alternatives for composites to demonstrate advantages.
Simulation/ Predictability	• Life-cycle predictive tools o The perception that composite chemistries and materials are so complex that life-cycle inventory data are difficult to develop is a barrier for which the 90:10 rule can go a long way to eliminate. • Modeling predictive tools o Cost of material characterization for modeling inputs. o Perception that there are too many variables to include in a model is a barrier to use of these tools. o The absence of a robust tool to relate the response of the formed part under specified boundary conditions and applied loads to the forming process used to manufacture the part. o Lack of predictability in final-part quality made with automated processes limits use of such tools. o Lack of performance predictability. ▪ Impact, crash, normal operating conditions, other accident conditions o Lack of ability to model residual stress in formed part. o Lack of ability to model stochastic materials. ▪ Variability of fiber orientation, variability of damage etc. o Lack of availability of mold flow simulations. o Gaps in ability to characterize thermomechanical changes in a material. o Gaps in ability to characterize UV changes in a material. o Lack of models for a material that has been recycled. o Challenges associated with rate-dependent behavior in processing and performance. o Lack of predictive manufacturing models causes composite parts to be high-risk to manufacture.

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Actionable Tasks to Advance Composites Manufacturing in the U.S.	
Near-Term (2016–2020)	
Infrastructure	• Life-cycle predictive tools o Create a life-cycle inventory database of current composite (such as resins, hardeners, fibers, etc.). This might be of the order of 100 representative chemicals and materials. Resources needed $200-300K. • Modeling predictive tools o Identify and publicize universities that have online training and license access. o Investigate potential for professional societies to allow members access to software and training.
Education and Training	• Life-cycle predictive tools o Develop tools for rapid industrial use of life-cycle information o Work with industrial and educational personnel to utilize available lci information • Modeling predictive tools o Consider offering consulting expertise as a shared resource. o Develop degree programs at universities. ▪ Focus on specific composites courses ▪ Include modules in existing courses
Standards	• Modeling predictive tools o Identify applicable standards committees. o Begin to develop relationships with applicable standards committees. o Develop universal standards for databases and predictive modeling tools so they are widely understood. o Establish of material standards. o Develop improved databases from data obtained from lower-variability material and processing conditions to improve accuracy of predictive modeling.
Demonstration	• Life-cycle predictive tools o Workshops on use of predictive tools o Publish case studies of composite products using life cycle analysis • Modeling predictive tools o Workshops on use of predictive tools o Continue to publish and present state-of-the art research related to development and use of predictive tools. o Identify and develop missing data for crashworthiness. o Identify validated models for crashworthiness. o Identify challenges in design-manufacturing-performance modeling. o Identify demonstration projects to help address deficiencies in predictive modeling tools and improve those tools. o Investigate Micro-mesh / Nano-mesh and include: ▪ Validated model ▪ Multi-loaded ▪ Database ▪ Environmental ▪ Failure Modes ▪ Primer ▪ University / Lab project

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Research	• Modeling predictive tools o Continue research related to development and use of predictive tools. ▪ Improve predictability ▪ Decrease time-to-market o Pursue new related areas of research identified by manufacturers through continued discussions at FIBERS events. o Improve accuracy of existing models through incorporation of physics into the simulations. o Develop models linking manufacturing to performance. ▪ Inclusion of physics and order of operations o Develop 3D multi-load multi-axis models o Investigate current methods for topology optimization and plan improvements to these methods. o Develop models for micro- and macro-scale simulations of joints. o Develop knowledge of chemistry including: ▪ Shear gradient ▪ Modified polymers for increased bonding capability ▪ Smart bond materials o Enhancements to knowledge of NDE including: ▪ Large scale ▪ Restricted access ▪ Reduce cost capital
Government Advocacy	• Modeling predictive tools o Investigate potential for MEPs to have the software and form a network. o Transition Reliable Unitized STructure (TRUST) project, part of the Defense Advanced Research Projects Agency's (DARPA) Open Manufacturing (OM) program
Design	• Life-cycle predictive tools o Create links with new developments in composites • Modeling predictive tools o Continue to improve design tools with ease-of-use in mind. o Identify common areas where design tools can be improved. o Integrate design analysis with supply chain, manufacturing and variables while addressing: ▪ Affordability ▪ Validation ▪ Both short and continuous fiber composites ▪ Output uniformity
Sustainability	• Life-cycle predictive tools o Integrate life-cycle predictive results with corporate sustainability programs and provide information to customers.
Simulation/ Predictability	• Life-cycle predictive tools o Expand predictive tools to examine large-scale market and product systems. • Modeling predictive systems o Continue to improve upon existing models for simulations to increase predictability of processes and material behavior. o Determine methodology for analysis of stochastic material including: ▪ Necessary material properties ▪ Process model ▪ Design model ▪ Manufacturing defect model ▪ Repair model ▪ Impact damage model including isolated (hail) and crush o Also, see Demonstration section above.

Mid-Term Actions (2020–2025)	
Infrastructure	• Life-cycle predictive tools o Expand the life cycle database to include the actual manufacturing of composites using a variety of techniques and machines with associated consumables. A life-cycle inventory database for these will be created to allow baseline comparison of technologies. This might be of the order of 10 representative composite forming processes and 50 consumables. Resources needed $200-300K • Modeling predictive tools o Expand upon identified universities that have online training and license access. o Develop a clearinghouse for part-time usage of predictive tools.
Education and Training	• Life-cycle predictive tools o Expand the industrial collaboration to include machine and consumable manufacturers as a means to best represent these technologies o Workshops for composite industry to utilize life-cycle tools • Modeling predictive tools o Consider workshops based on common needs discovered during near-term activities. Can be done in conjunction with demonstration activities. o Continue to improve upon the education and training activities begun during previous period. o Continue development of degree programs at universities. ▪ Focus on specific composites courses ▪ Include modules in existing courses
Standards	• Life-cycle predictive tools o Development of subcomponent testing to eliminate need for full-scale certification of new composite material systems. • Modeling predictive tools o Become increasingly involved with the work of applicable standards committees to support their work in updating applicable standards. o Determine standards for validating existing models with experimental data. o Continue to develop and enhance standard material database.
Demonstration	• Life-cycle predictive tools o Field studies to refine composite manufacturing predictive tools o Explore new composite manufacturing processes in developmental stage • Modeling predictive tools o Begin to address challenges in design-manufacturing-performance modeling. o Continue to improve upon the demonstration activities begun during previous period. o Identify and complete additional demonstration projects not addressed in prior period.
Research	Modeling predictive tools o Continue research related to development and use of predictive tools and include related areas of research identified in previous term. o Implement improvements to topology optimization models. o Continue to identify related areas of research identified by manufacturers through continued discussions at FIBERS events.
Government Advocacy	• Life-cycle predictive tools o Support development of subcomponent testing methods to eliminate need for full-scale certification of new composite material systems. • Modeling predictive tools o Continue to improve upon the government advocacy activities begun during previous period.
Design	• Life-cycle predictive tools o Provide feedback and workshops for equipment and consumables manufacturers to approach improvements in composite manufacturing processes. • Modeling predictive tools o Continue to improve upon the design activities begun during previous period.

Sustainability	• Life-cycle predictive tools o Integrate life-cycle predictive results with corporate sustainability programs and provide information to customers
Simulation/ Predictability	• Life-cycle predictive tools o Begin analysis and simulation of new composite manufacturing technologies and tools as automation increases to establish the environmental improvement of these alternatives at full scale. • Modeling predictive tools o Continue to improve upon the activities related to predictability of simulations begun during previous period. o Determine methodology for analysis of stochastic material including: ▪ Performance after impact and repair ▪ Prediction of fiber orientation

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Long-Term Actions (2026–2030+)	

Infrastructure	• Life-cycle predictive tools
	  o Add to the life cycle database more advanced materials, such as biobased resins, fibers, and viscosity reducers will be more mature and the life cycle predictive tools will add these to the information base available to composite manufacturers and suppliers. This might be of the order of 50 representative chemicals and materials. Resources needed $200-300K
	• Modeling predictive tools
	  o Continue to improve upon the infrastructure activities begun during previous periods.

Education and Training	• Life-cycle predictive tools
	  o Continue the dissemination and training of previous periods.
	• Modeling predictive tools
	  o Continue to improve upon the education and training begun during the previous periods.

Standards	• Modeling predictive tools o Continue to improve upon the involvement with applicable standards committees begun during the previous periods.

Demonstration	• Life-cycle predictive tools
	  o Continue the publication and workshops to engage industry with these new materials for composites.
	• Modeling predictive tools
	  o Continue to improve upon the demonstration activities begun during the previous periods.

Research	• Modeling predictive tools o Continue to improve upon the research activities begun during the previous periods.
Government Advocacy	• Modeling predictive tools o Continue to improve upon the government advocacy activities begun during the previous periods.

Design	• Life-cycle predictive tools
	  o Evaluate the utilization processes adopted by the composites industry to improve the use of life-cycle predictive tools
	• Modeling predictive tools
	  o Continue to improve upon the design activities begun during previous periods.

Sustainability	• Life-cycle predictive tools o Integrate life-cycle predictive results with corporate sustainability programs and provide information to customers

Simulation/ Predictability	• Life-cycle predictive tools
	  o Continue the processes of previous periods and expand the analysis of barriers to use of life-cycle tools.
	• Modeling predictive tools
	  o Continue to improve upon predictability of simulations begun during previous periods.

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Developing a Skilled Workforce

Drivers by Stakeholders	
Industry	• Industry growth requires new employees to be trained in the composites sector • Increased automation requires education in automation and code development • New market segments in infrastructure and architecture require workers familiar with these industries • Industry support can guide the development of relevant educational programs • Existing workforce needs to be trained in new processes and technologies • Reduce turnover • Need familiarity with standards • Require ability to write and follow SOP's (standard operating procedures) • Need to abide by industry standards of Lean Protocols and process engineering / manufacturing statistics • Quality control requires adherence to existing standards and manufacturing best practices
Educational Institutions	• Perceived need to replace artisan, experience-based design with rational, scientific-based design • Benefits of reduced trial-and-error approaches due to inexperience of workforce • Need computational knowledge in addition to physical manufacture skills • Address the material set requirements and design requirements in education • Industry engagement and input via regular contact, Industrial Advisory Boards
Non-Profit Organizations	• Professional society support can guide and develop new educational programs • Standards bodies (e.g., ASTM, ISO, SAMPE)
Government & Policy	• Government emphasis on manufacturing education drives educators to support industry • Government regulations on labor force, environmental impacts

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Common Barriers	
Industry Recruitment	• Reliance on status quo from high schools, community colleges, local shops and apprenticeships can provide insufficient employees for industry needs • Intermittent engagement with educational institutions can result in poor supply of qualified personnel • Defined industry needs are not incorporated into some workforce development programs due to limited communication and engagement with educators • Industry partners can have difficulty defining their present and future needs • Variability in industrial processes leads to difficulty in training relevant to industry • Engineering acceptance of composite materials has improved, but lack of experience and expertise among designers and manufacturers is still a limiting factor
Industry Retention & Mobility	• Poor retention of qualified personnel (~1 out of 40 remaining in composites industry) • Transfer of qualified personnel into other industry sectors leaves skills shortages in composites industry • Salary ranges for the various position descriptions vary widely by sector and therefore result in retention issues • Mobility of qualified personnel is frequently low, such that workforce remains local and will not relocate to new job sites • Lack of diversity • Generations of engineers that understand the composites formulations are retiring without their knowledge transferred to a new generation of engineers • There is an unavailability of human resources to perform internal research and development, even though production equipment is available
High School-Level Education and Training	• Minimal exposure to the concept of composites leads to poor name recognition among students in subsequent education and career options • Lack of promotional materials, knowledge among high school career counselors • High school alternative workforce development programs lack composites programs • Vocational training programs lack composites options • Shortage of workforce educated in basic composite manufacturing processes leading to increased on-the-job training time • Skilled positions such as CNC operator, mix room operator, and repair of composites require additional training
Community College-Level Education	• Academic institutions need to seek industry input regarding student training and involve industry in curriculum design. • Few two-year institutions offer a formal degree in composites • Difficult and ill-defined pathways to matriculate from a community college into a B.S.-level program • Shortage of workforce educated in basic composite manufacturing processes leading to increased on-the-job training time • Lack of project and process management standards for engineering problem solving • Lack of U.S. mentoring and training programs, and there is no financial incentives to develop such programs • Retention of skilled instructional personnel is difficult due to pay and workload

University-Level Education	• Academic institutions need to seek industry input regarding student training • Few institutions offer a formal degree in composites • Industry fear to hire advanced degree (M.S., Ph.D.) students without practical knowledge, who therefore need more real world experience • Industry wishes for education that targets manufacturing engineering skill sets vs. purely theoretical bases. Examples are process statistics, engineering problem solving and lean manufacturing • Difficult and ill-defined pathways to matriculate from a community college into a B.S.-level program • Shortage of trained engineers with expertise in manufacturing processes, automation and robotics • Existing programs have been developed independently, and therefore do not have defined commonalities of education or industry target training
Non-Profit Organizations	• Develop or utilize existing certification of technicians • Programs that are producing results are the ACC teaching program and the composites program at Winona State, but more technicians need to be trained as ACMA-CCT
Government & Policy	• Existing educational programs are insufficiently available and oversubscribed • Present lack of support for apprenticeship programs • Government-funded research topics are sometimes not relevant to identified market needs, thereby decreasing students' relevance to industry and the probability of hire after graduation • Applied research dictated by industry needs on a commercial schedule • Need investment training facilities that contain industrially relevant equipment, particularly with the growth in automated equipment and other capital-intensive equipment

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Actionable Tasks in Workforce Development for Composites Manufacturing in the U.S.	
Near-Term (2015–2020)	
Industry	• Active industry outreach to collaborate with and fund academic institutions for training development • Recruit high school students to composites career paths • Improve access for training of existing employees by means of financial and time support • Increase funding for applied research and development leading to commercialization and new products
Cross-Cutting Academic	• Generate vertical pathways from HS, Community College, through four year university programs directly structured around composites manufacturing
High School-Level Education	• Investigate the incorporation of composites within high school curricula and vocational programs • Document existing manufacturing project and provide as training material
Community College-Level Education	• Develop certification programs that are based on industry input • Investigate the development of 6-month training programs • Expand the number of composite training programs within community colleges • Emphasize practice with hands-on skills • Investigate options for continuous improvement and flexible adaptation to new technologies • Emphasize basic process manufacturing technician skill sets to include manufacturing statistics (SPC), documentation skills, and Lean Manufacturing
University-Level Education	• Develop certification programs that are based on industry input • Develop specializations within curricula to produce certified/degreed personnel • Emphasize practice with hands-on skills • Develop modular programs that focus on cores of information at different levels or integrate information modules into existing courses • Students should be engaged at all levels of industrial research projects • Professors should be familiar with industrial processes and the needs of industry through active engagement, site visits, and joint research projects • Create short term engineering-focused projects that match industry quarterly time requirements. Deliver to industry the data when they need it on their time cycle
Non-profit Organizations	• Develop a certified curriculum for schools which would promote uniform skills for graduates across the country • Create additional certification (e.g., CCT) and standards relevant to training
Government Advocacy	• Encourage state and federal governments to invest in new composite programs that are useful to industry, enhance competitiveness and lead to commercialization • Work with the different sectors to define workforce skill set requirements • Create industry-driven applied research facilities, and reduce throughput time on applied research needs of industry

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Mid-Term Actions (2020–2025)	
Industry	- Develop multi-year collaborations with academic institutions for sustainable applied research and development efforts
Academic Organizations	- Establish university and community college sites outfitted with equipment and facilities accessible to industry or jointly owned and maintained by industry - Launch next generation process and material improvement for recyclability, green process and engineered material properties
Non-profit Organizations	- Implement a standardized curriculum within vocational schools and community colleges designed in collaboration with industry
Government Advocacy	- Develop government-funded research centers targeted to new product and process development clustered around key market opportunities - Coordination of applied research and development by federal agencies with industry market development

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Appendix C

The following is a list of ideas for Demonstration Projects that were identified during the Roadmapping activities. Each of these projects has one or more aspects that could assist to advance the state of the Composites Manufacturing industry in the U.S.

1. Demonstrate low-cost and low-quantity manufacturing of high-temperature thermoplastic components by developing flexible high-temperature molds and alternative manufacturing methods.

2. Demonstrate recycling of composites from millions of cars made from composites by turning recycled cars into usable commodity.

3. Demonstration project to address the fire performance of components through the development of lower cost material and processes.

4. Demonstrate the durability of composites through the development of erosion resistant coatings for the leading edge.

5. Demonstrate use of composites in structures for various applications with improved interfaces of conductors within the composites, development of 20+-year durability and improved bonding of different materials.

6. Demonstrate time to market for new materials and processes through the development of prediction tools and credible models, as well as new manufacturing methods for better QA/QC.

7. Demonstrate predictive modeling with the linking of manufacturing and performance, development of a materials database and inclusion of physics and order of operations.

8. Initiative for state offices to offer modeling services and access to software, partnering with NIST and MEPS.

9. Initiative to improve low-variability manufacturing through the development of strict material quality control standards for feedstock materials, improved databases from data developed from lower-variability material and processing conditions for more accurate predictive modeling and universal standards for databases and predictive modeling tools so they are universally standard.

10. Initiative to provide adequate material properties through the development of a material properties database and materials and manufacturing models to feed performance prediction models.

11. Demonstration of manufacturing and reparability issues through understanding the sources of variability for given processing methods, identification of low-cost NDE methods and repair methods, development of skilled workforce for the manufacturing and repair of composites and development of regulations up front for repair and supportability.

12. Urban mobility demonstration concept that addresses lack of design tools for crashworthiness, multi-material joining, balance of material value and performance.

13. Autonomous vehicle concept that would be designed from the bottom up with composite materials, use new and innovative subsystem designs, and establishes new standards.

14. B-pillar project that demonstrates smart material utilization, cost-efficient manufacture through automation to address high volume and validation through modeling.

15. Composite automotive material project to demonstrate high-rate production with low variability and acceptable attributes through an integrated approach for material characterization, simulation, validation and NDE.

16. Design of a lightweight automotive panel (hood) using high-stiffness chopped fiber to achieve weight and cost savings in a high-volume production with low part-to-part variability and capable of E-coat process.

17. Initiative to develop undergraduate education modules to ensure that graduating engineers have a knowledge and willingness to expand the use of composites in engineering design.

18. Demonstrate a methodology of user-friendly process simulation with sensors for smart, rapid manufacturing of winglets, and aerospace part with high turnover in the design, bottlenecks in production, and complex geometries.

19. Flexible automation that can enable the use of automation for low production rate quantities by lowering the upfront capital needed.

20. Research into fiber/resin interface and the coatings/sizings that can be added to fibers to improve impact/crack resistance.

21. Fire resistant resin for construction issues that is not toxic when burned.

22. Enabling knowledge sharing means for composite tooling/production process expertise amongst the industry because it is, and will still be in the long term, an obstacle to the progress of composite manufacturing.

23. Developing lower cost and more efficient resin matrices for use in pultrusion applications.

24. Reduce in and part-to-part variations for SMC and LCM compression molding.

25. Automated and semi-automated complex lightweight sandwich manufacturing methods.

26. Create a comprehensive database that would allow users to select different fiber types for specific applications based on an extensive battery of test results/properties. Right now it’s hard to compare different materials that aren’t tested equivalently.

27. High pressure composite storage tanks for bulk transportation.

28. Sharing of failure cause analysis throughout the industry from a central data base.

29. Tables for material substitution (resins, fibers).

30. Development of exterior panels for commercial buildings. Need long term durability, reduced energy consumption for the building, ease of installation and cost competitive with insulated metal panels. Something that looks and feels like stone or brick would be ideal.

31. Fire resistant resin technology to compete in commercial building construction and UV resistance of FRP composites without the need of painting/coating.

32. Introduce at the high school level a fundamentals/introduction to composites. Impress upon the participants the importance of “Personal Protective Gear”; Vocabulary and bagging skills. With these covered a young person could apply/get a job and survive for a full career.

33. Demonstration of in-field joining techniques for segmented wind turbine blades.

34. Demonstration of nonpetroleum-based resins for improved sustainability and recyclability of wind turbine blades.