Oak Ridge National Laboratory

U.S. DEPARTMENT OF ENERGY

# Low Cost Carbon Fiber Composites for Energy Applications

## Workshop Results

March 3-4, 2009 • Oak Ridge, Tennessee




# Table of Contents

# Table of Acronyms

BAA – Broad Agency Announcement

CVD – Chemical Vapor Deposition

DOE – Department of Energy

DSC – Differential Scanning Calorimetry

EAR – Export Administration Regulations

EERE – Energy Efficiency and Renewable Energy

FEA – Finite Element Analysis

GC – Gas Chromatography

IP – Intellectual property

ITAR – International Trafficking in Arms Regulations

LLDPE – Linear Low Density Polyethylene

LOI – Limiting Oxygen Index

MAP – Microwave Assisted Plasma

MIT – Multiple Insert Tooling

MS – Mass Spectroscopy

ORNL – Oak Ridge National Laboratory

P4 – Programmable Powdered Preform Process

PAN – Polyacrylonitrile

PO – Polyolefin

QA – Quality Assurance

R&D – Research and Development

RD&D – Research, Development, and Demonstration

ROI – Return on Investment

RT – Residence Time

RTM – Resin-Transfer Molding

SBIR – Small Business Innovation Research

SEM – Scanning Electron Microscopy

SMC – Sheet Molding Compound

SRIM – Structural Reaction Injection Molding

TEM – Transmission Electron Microscopy

TGA – Thermogravimetric Analysis

UV – Ultraviolet

VE – Vinyl Ester

ZIP – Zero Injection Pressure

# Executive Summary

On March 3-4, 2009, more than 75 stakeholders in various aspects of carbon fiber composites including materials and parts developers, end users, and experts from government, academia and industry (including the wind, automotive, forest products, oil and gas, and chemical industries) attended an invitation-only workshop at the Oak Ridge National Laboratory (ORNL). The workshop focused on defining the research, development, and demonstration (RD&D) and business-related needs that will enable the development and commercialization of low-cost carbon fibers and their composites for energy applications. Following is an overview of the major findings and a list of possible next steps.

**Major Findings**

- The development of low-cost materials for any of the steps leading to carbon fiber composite manufacturing is interdependent with other steps. For example, when identifying a low-cost precursor, it is important to consider not only the properties of the carbon fiber that it becomes, but also its compatibility with fiber coatings, matrix resins, composite development, and parts manufacturing. RD&D cannot be defined in a vacuum. Using a systems approach enables consideration of the interactions among several disciplines.
- Because of the energy implications on different sectors, the development of a domestic carbon fiber composite industry is a strategic national priority. But many of the fiber property (including cost) requirements are end product-dependent, which can lead to a stovepipe situation. Over-specification will drive cost up. We need a major initiative that will result in a consortium, with everyone working together in a focused group.
- Although several applications for carbon fiber composites are currently possible (i.e., energy storage system, rollers in paper converting, electric transmission cables), they haven't been implemented due to the lack in stability of pricing and availability.
- Identifying/developing the optimum low-cost carbon fiber precursors and processes for both high- and low-strength fiber remains a high-priority issue.
- The interface between the carbon fiber and the matrix resin is a very important part in developing carbon fiber composites. Surface treatment and sizing for the carbon fiber are critical needs if the fibers are going to be compatible with low-cost matrix resin. There are, however, few techniques available to characterize and model these interfaces. This inhibits the development of mass production processes. A catalogue of best practices for this step is needed.
- Cost and return on investment (ROI) are critical concerns. "Leaning" of the value chain (eliminating waste or non-value-added activities) can help reduce costs and raise ROI.
- Risk must be reduced in order to make the products attractive to market. Incentives and a reduction in regulatory barriers - one step would be the development of technical standards - can help in reducing risk.
- A systems approach could be addressed by developing **vertically integrated teams**. Such a team would be built with an end product in mind; the "voice of the customer" will drive the direction of needs and requirements. This would provide a feedback mechanism where, for instance, composite manufacturers would have input into development of a low-cost carbon-

fiber precursor. With a vertically integrated team, technologies known by a team member can be utilized quickly, as information is shared. This reduces and distributes the risk, improves efficiency, allows production at volumes sufficient for product development, and enables a quicker path to commercialization. The vertically integrated approach, however, requires significant coordination to solve issues such as intellectual property (IP) rights, budget (who will pay for what), and schedule. Requirements will likely differ for each member organization. In addition, it can easily result in a stove-piping situation geared toward one or a few end products. Finally, its high visibility could backfire if the team fails.

- A **demonstration facility*** (perhaps a national demonstration facility) housed with both equipment and staff could be made available to a variety of researchers and developers. This facility would provide access to capital equipment, would allow resource sharing, and would mitigate risk and reduce cost to the individual entity. The single location with a large number of experts present would speed development of carbon fiber and composites, as it would be able to address all of the steps in the process and would be able to cover several iterative tests rapidly. It would allow comparison of competing technologies in a single location. It would also provide a place for discussion, networking, and exchange of ideas. However, the facility would require a large capital investment, long-term funding might be difficult to obtain, and managing IP would be difficult. It is unlikely that all the important technologies, including some state-of-the-art technologies, would be available at the facility.
- The **horizontally integrated approach** lacks the systems concept that is basically at the center of the other approaches. It focuses on a key technology or technologies, and thereby increases the possibility of success for that technology. It is smaller in scale and simpler to implement than the other approaches, and is therefore a viable option for a single organization with limited resources. It can also focus on the point of the value chain that has the highest potential. There is already a mechanism for the government to provide stimulus in the forms of Small Business Innovation Research (SBIR) and Broad Agency Announcements (BAA). In fact, the Department of Energy (DOE) is already implementing these, but it can be a time-consuming administrative burden. Another disadvantage of the horizontal approach is that it only looks at a small number of possibilities and interactions. It may actually be considered a distraction to the systems approach.
- A **government-industry cost share approach** would allow a call for proposals and could leverage SBIR. In this scenario, the risks would be shared. This would stimulate several companies and make it easier to uphold intellectual properties. It would allow foreign companies to participate and therefore invest in the U.S. economy. Free enterprise would take its course and strategic partnerships would be developed. However, the private sector may not take advantage of this approach if it were inadequately funded.
- A **two-phase rapid-scale up approach** would include a first phase focused on pilot-scale production and would target the validation and verification of emerging technologies. It would include a highly modular facility, incorporate existing and emerging technologies, and produce a substantial amount of carbon fiber. The second phase would focus on scale-up to full production and would target the application of the technologies into various end products such as automotive, wind, aerospace, etc. It would include a capability to build a two million pound line subsidized by the Federal Government and supported by key partners

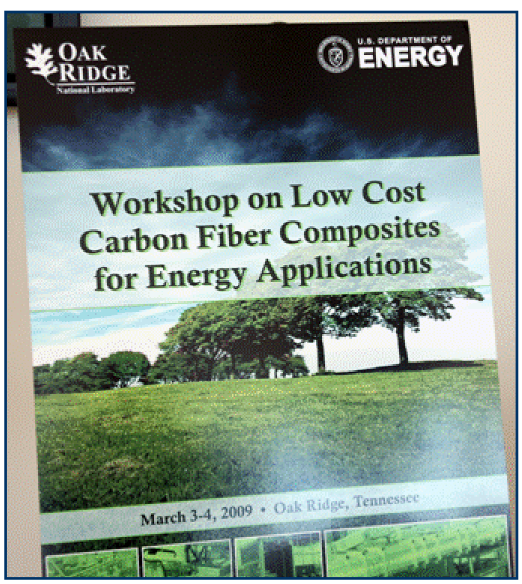
---

*This facility was sometimes referred to as a "user facility" during the workshop. However, since that term may have a different meaning to DOE than was implied in the workshop, the decision was made to use the term "demonstration facility" in this document.

of the industry. Such an approach has the potential for breakthrough. It would mitigate risk, allow a rapid scale-up, and validate and quantify cost advantages. It would, however, require a very large flexible facility and commitment from all parties. IP protection would be difficult. Most important, participation by carbon fiber companies might be limited if the approach is viewed as a threat to their industry.

**Actions, Next Steps**

- Currently, carbon fiber end users are composed of a diverse group of stakeholders that are fragmented. These stakeholders should collaborate and discuss their requirements so that there is an approach for widespread use of carbon fiber. Incentives are needed for this. The DOE can play a key role to help facilitate this collaboration.
- The DOE programs with stake in carbon fiber composite products should develop a roadmap that includes a clear list of metrics and objectives and an action plan as to how they can be achieved. Targets and benchmarks are necessary in order to define where we need to go and how we are progressing. It is important that the roadmap indicate specifically what the short- and mid-term objectives are. Some of the benefit is achieved through something that is developed along the way, not just the end-target.
- While the automotive and wind industries are primary targets for low-cost carbon fiber composites in the energy field, investigating other applications such as electrical transmission and distribution lines, oil rigs, and airplanes should be pursued.
- Cost per pound of carbon fiber in itself is not necessarily a proper target. One suggestion is cost per pound of end-use application, perhaps in terms, for instance, of dollars saved per vehicle, or per kWh of electricity.
- Understanding carbon fiber composite status and needs on a global scale would be of importance.
- It would be useful to conduct a survey based on the results from the workshop to get additional feedback and perspectives and convene a follow-up workshop in one to two years that would "keep the momentum going" in this research area.



# Keys for Breakout Group Tables

This page explains the symbols and abbreviations used in the Tables in the Breakout Group chapters (Chapters 1-4) of this Report.

**<u>Explanation for symbol</u>**:

◆ In sessions where prioritization on a topic was requested, each participant cast 1 to 5 votes. Each vote cast is represented by this shape.

**<u>Explanation of abbreviations</u>**:

For the discussions of Priority RD&D Needs and Priority Market Issue Challenges some abbreviations and assumptions were used in the tables for "Timeframe", Partnership Strategies, and Resource Requirements as follows:

<u>Timeframe:</u>

Near term < 3 years
Mid term = 3-7 years
Long term > 7 years

<u>Partnership Strategies:</u>

I = Industry
G = Government
NL = National labs
U = Universities
NGO = Non Government Organizations (such as trade associations)

<u>Resource Requirements – for funding</u>:

Technical Breakout Groups:
Low: < $0.5M
Medium: $0.5 – 3M
High: > $3M

Business Breakout Group:
Low: < $1M
Medium: $1 – 10M
High: > $10M

In some cases, the participants chose to use a timeframe and/or funding level that is not in line with this key. In those cases, the actual timeframe and/or funding dollar amount are shown in the tables.

# Introduction

On March 3-4, 2009, the Oak Ridge National Laboratory (ORNL), on behalf of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), hosted an invitation-only workshop on Low Cost Carbon Fiber Composites for Energy Applications in Oak Ridge, Tennessee. The workshop focused on the research, development, and demonstration (RD&D) and business-related needs that will enable the development and commercialization of low-cost carbon fibers and their composites.

The workshop brought together more than 75 developers, end users and experts from government, academia, and industry (including the wind, automotive, forest products, oil and gas, and chemical industries) who are, in one way or another, stakeholders for low-cost carbon fiber composites. The purpose of the workshop was to identify the critical needs to develop and commercialize carbon fiber composites in energy-related areas, identify the steps and details necessary to address these needs, and to identify potential mechanisms by which the process could be most effectively realized.

The 1 ½-day workshop began with welcoming messages from ORNL and DOE and moved into a plenary session that included presentations by several experts from industry and the national laboratories on carbon fiber and composite development and applications:

- Mohamed Abdallah, *President, MGA Advanced Composites and Engineering Co.,* "History and Status of Carbon Fiber Composites"
- C. David Warren, *Manager, Transportation Materials Program, Oak Ridge National Laboratory,* "Carbon Fiber Composites Technology Development"
- Jim deVries, *Staff Technical Expert, Research and Innovation Center, Ford Motor Company,* "Carbon Fiber in the Automotive Industry... The Holy Grail or Reality?"
- Jose Zayas, *Manager, Wind Energy, Sandia National Laboratory,* "Technology Innovation for Wind Energy: Carbon Fiber"
- Scott Finn, *Chief Engineer of Composites, GE Research,* "General Industrial Applications"

Scott Finn, *Chief Engineer of Composites, GE Research*, presents "General Industrial Applications" during the plenary session

The workshop participants were divided into four breakout groups, three working in parallel on a technical track to address RD&D needs, and the fourth working on a business track to address scale-up and deployment needs. Technical track participants addressed the following:

1) What are the RD&D needs required to lower the costs of carbon fiber reinforced composites?

2) What are the key activities, timeframes, partnering strategies, and resource requirements to address the top priority technical needs?
3) What are the potential approaches that can be implemented to address the priority needs?

Business track participants utilized the following focus questions:

1) What are the market issues and challenges associated with large-scale deployment and manufacturing scale-up for key applications?
2) What are the key deployment and scale-up activities, timeframes, partnering strategies and resource requirements to address the top priority market issues and challenges?
3) What are the potential approaches that can be implemented to address the priority issues and challenges?

Chapters 1 through 4 summarize the discussions that took place in the four breakout groups.

Following the breakout group sessions, a closing plenary session was held. This consisted of reports from the four breakout groups and a presentation, "Advancing Technology Deployment through Industry-Government Partnerships," by Alan Liby, Manager, ORNL Industrial and Economic Development Partnerships. Workshop participants provided final thoughts and proposed next steps for the low-cost carbon fiber composite constituents and stakeholders. These final thoughts are summarized in Chapter 5.

Appendix A provides the workshop agenda, while Appendix B provides a list of the workshop participants. Appendix C provides contact information for the workshop coordination team.

Opening and closing plenary session presentations are available at:
http://www.ms.ornl.gov/PMC/carbon_fiber09/index.html

# 1. Technical Breakout Group # 1

Carbon fiber composites are being used in a number of different applications in the aerospace, recreation, civil infrastructure and other industries. It is also an enabling material for improved performance in energy-related applications. However, it is too expensive for widespread utilization in most high-volume applications. In addition, the methods for manufacturing carbon fiber reinforced composite structures tend to be slow, labor intensive, and inconsistent in resulting product quality. There are several key research and development (R&D) needs that should be addressed in order to further the development of lower cost carbon fiber composites.

**Major Findings, Caveats, Key Issues**

- Low-cost materials are interdependent from precursor through life-cycle cost and integration (systems approach)
- The processes require interaction among many disciplines
- Diversity of the process of composite parts manufacturing makes cost analysis difficult
- Most of the higher temperature chemistry of carbon fiber is not well understood
- There are few techniques to characterize and model interfaces, which is a barrier to mass production
- Cataloging the best practices of fiber/matrix interface is needed
- There needs to be a breakthrough in the precursor and in the processes to make the carbon fiber lower cost (for low- and high-strength carbon fiber)

One of the key R&D needs for lower cost carbon fiber composites is a significant breakthrough in the precursor material. One of the first steps to approach this is to start developing the fundamental knowledge of carbon precursor structure and property relationships. This can be accomplished by starting a literature search to compile the state-of-the-art of carbon fiber forming from polymer precursor candidates. These candidates can then be "fingerprinted" analytically to determine the potential yield based on crosslinking and chain scission fragmentation. The fragmentation reaction mechanisms and kinetics can then be determined to tailor the stabilization approach.

Another key R&D need is a breakthrough in the processes to make carbon fiber composites. The development of faster automated process and technologies for parts production is needed. The use of process investigation using techniques such as multiple insert tooling (MIT) and zero injection pressure can help to improve production speed. Another aspect that can help to improve process times is developing materials that have fast cure methods using catalysts so that they spend less time in the mold, while not heating too quickly.

An additional key R&D need is to reduce the labor content by automation. One of the activities that can be conducted to help with this need is to use computer-engineered modeling of carbon fiber process for labor versus automation. Developing these models can help to demonstrate what the benefits are for tasks such as automation of loading of precursor spools and post pre-pregging operation; cutting, stitching, layup. An additional component that can lead to increased labor is when ovens need to be cleared of high levels of toxic gases or other unwanted gasses during the curing process. This increases the amount of labor necessary and increases the process time. If there were automated sensors in ovens, they could help to detect toxic gases that can cause problems before things get out of control.

Several approaches were considered to determine the most effective methodology to implement the RD&D needed to address low-cost carbon fiber composites. One approach discussed was establishing a "national demonstration facility" where equipment and staff could be available to enable researchers and developers to work more efficiently on their products. A second approach involved the establishment of a horizontally integrated team to develop advanced technologies at specific points in the value stream. A third approach is to "develop vertically integrated demonstration projects" where a team has expertise at each step along the way, from fiber precursor to finished composite part.

The national demonstration facility would be available to all interested stakeholders. Equipment and staff could be available to enable researchers and developers to work more efficiently on their products. The national demonstration facility implementation approach has the advantage of being able to access a lot of equipment located in the same place so that it will help to increase the speed of development. This facility will also have resident technical experts to monitor and operate the facility. It can serve as a training ground for students and visiting staff and teach best practices. However, this type of facility may not be able to house all the key R&D equipment, some of which may not be state-of-the-art.

### Approach 1 – "National Demonstration Facility"

**Advantages**

- Having everything co-located will help to increase speed of development
- Having critical mass of technical experts
- Able to conduct testing iterations very quickly-can evaluate a number of precursors and process technologies

**Disadvantages**

- Not able to have all important technologies located at facility
- May not be state-of-the-art
- Integration will be complicated; setup will be slower because of flexibility

A horizontally integrated team will develop advanced technologies at a designated step within the process of carbon fiber composite development. This implementation approach is simpler to implement and smaller in scale compared to other approaches. It allows for a very detailed amount of information to be collected about one particular component of the development of carbon fiber composites. Collaborations with other groups that are working on R&D of other components in the process chain will be key so that the information collected here is applied to the other steps in the process. One of the disadvantages for this approach is that it would only incrementally advance the technology because it is not looking at all the possibilities and interactions with other aspects of the system. This is a potential issue considering that the industry is looking for opportunities that will have the potential for a significant leap forward in developing low-cost carbon fiber composites.

### Approach 2 – "Develop Advanced Technologies at Specific Points within Value Stream"

**Advantages**

- Much smaller scale and simpler to implement than approach #1 and #3
- Requires development of a polished or more focused concept

**Disadvantages**

- Only a small jump forward—not looking at all possibilities and interactions

The third implementation approach that was discussed was the development of vertically integrated demonstration projects. This approach uncovers opportunities for total system improvements with a feedback mechanism. This approach also optimizes the existing technologies and has the greatest potential of reaping the most benefits in the short term. One of the challenges with this approach is determining who will pay for it. For instance, some stakeholders may be interested in certain aspects of the system such as the front end or precursor development stage while others may be more interested in the back end of the system.

### Approach 3 – "Develop Vertically Integrated Demonstration Projects"

**Advantages**

- Uncovers opportunities for total system improvement with a feedback mechanism
- Optimizes the existing technologies—getting the most out of the short term

**Disadvantages**

- Determining who will pay for approach (some organizations interested in front end, others are interested in back end)
- Different requirements from different industries and stakeholders

**Table 1-1. List of Participants**

| Name | Organization |
|---|---|
| Peter Axegard | STFI-Packforsk |
| Paul Bencin | C.A. Litzler |
| Doug Bradley | General Dynamics |
| David Hartman | Owens Corning |
| Dave Icke (Breakout Group Reporter) | Advanced Electron Beams |
| Ryutaro Izumi | Izumi International, Inc |
| John Koenig | Southern Research |
| Gary Lownsdale | Plasan Carbon Composites |
| Eric Leonard | Toyota Technical Center, USA |
| Steven Olsen | GE Wind |
| Felix Paulauskas | ORNL |
| Kenneth Smith | Hexcel |
| Philip Smith | Eastman Chemical Company |
| Brian Marchionini (Facilitator) | Energetics Incorporated |

## Technical Breakout 1

### Table 1-2. What Are the RD&D Needs Required to Lower Costs of Carbon Fiber Reinforced Composites?

| Precursors | Processing Costs (Carbon Fiber) | Composite Process Cost | Life Cycle Cost | System |
|---|---|---|---|---|
| • Develop new conversion technologies and processes for precursors (pitch, organic polymers, Polyacrylonitrile [PAN], novel material)<br>◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆<br>• Need fundamental knowledge of carbon forming process-precursor dependencies<br>◆◆◆◆◆◆◆<br>• Low-cost material for the carbon fiber itself (precursor)<br>◆<br>• Applying latest differential scanning calorimetry (DSC) and thermo-gravimetric analysis (TGA) for iterative testing of precursors<br>• Pure lignin from pulp mills; low ash, sodium, silicon; low sugar<br>• Best tree/plant for lignin carbon fiber precursor<br>• Low-cost, high-quality lignin from pulp mills<br>• Need high-quality and consistent materials to allow more throughput on the line and improve scalability | • Process and automation breakthrough for scalable process<br>◆<br>• Reduce equipment energy cost for processing<br>◆<br>• Choppable product from low-cost sheet molding compound (SMC) | • Faster automated process and technologies for parts production<br>◆◆◆◆◆◆<br>• Lower material process costs at production scale for new applications<br>◆◆◆<br>• Need a technology breakthrough for the low-cost composite to work<br>◆◆◆<br>• Use the most basic raw materials directly in mold with zero scrap<br>◆◆<br>– Lower cost resin system – matrix management and cycle time reduction<br>◆◆<br>• Material design optimization balanced for lay-up/placement/cost; designing part to make it easier to make lay-up<br>◆<br>• How to get a class A finish without special treatments<br>• Cost reduction in composite generation processes | • Develop "re-carbon" or recycle strategy and define requirements<br>◆◆<br>• Develop repair technology and methodology for repair and be able to detect defects<br>• Non-destructive evaluation | • Reduced labor content using automation with smart feedback mechanism for fine tuning<br>◆◆◆◆◆◆<br>• Looking at capital investment cost on a total system basis<br>◆◆◆◆<br>• Identify technical bottlenecks/hurdles with pre-oxidation<br>◆◆◆◆<br>• Development of systems approach – making good choices for lower costs<br>◆◆◆<br>• Need a model for process scale up<br>◆◆<br>• Optimal properties and systems with public database<br>◆◆<br>• Raw material design fundamentals (toolbox); lignin to carbon fiber; resin to properties<br>• Need to value the entire system; oil-lignin-finished parts (a value steam "map")<br>• Detailed literature search on sizing optimization, pre-cursors<br>• Integration of the supply chain from raw material to finished part |

**Table 1-3. Priority RD&D Need: Fundamental Knowledge of Carbon Precursor Structure – Property Relationships**

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • Compile state-of-the-art carbon fiber forming from polymer precursor candidates; pyrolysis, chemical vapor deposition (CVD) | • 6 months | • Industrial suppliers of precursor and raw materials | • High-level literature review integration of CVD, PAN, and pitch (Lignin). Medium Funding |
| • Fingerprint analytically the potential yield based on crosslinking and chain scission fragmentation | • 18 months | • NL | • High-temperature analytical testing—TGA, DSC, mass spectroscopy (MS), gas chromatography (GC), scanning electron microscopy (SEM), transmission electron microscopy (TEM), Medium Funding |
| • Determine fragmentation reaction mechanisms and kinetics to tailor the stabilization approach | • 36 months | • NL, U | • Computational modeling and bench chemistry, Medium Funding |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 1

### Table 1-4. Priority RD&D Need: New Precursor Material and Process That Allows Lower Cost Carbon Fiber

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • Modified polyolefin (PO) precursor | • 2–3 years | • Supplier of PO and textile assets | • Raw materials<br>• $2–$4M |
| • Lignin compounds precursor | • 2–3 years | • Supplier of refined lignin life cycle stewardship | • Raw materials |
| • Fiber formation and stabilization to PAN benchmark | • Mid term | • NL, fiber supplier | • Pilot line |
| • Conversion from PAN to carbon fiber benchmark | • Mid term | • NL, fiber supplier | • Pilot line |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 1

### Table 1-5. Priority RD&D Need: Reduced Labor Content Using Automation With Smart Feedback

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements ~$30M |
|---|---|---|---|
| • Computer-engineered modeling of carbon fiber process for labor vs. automation | • Near term | • U lead, I, G | • Expertise, mid-level funding |
| • Automation of loading of precursor spools | • Mid term | • I lead, U | • Equipment, high-level funding |
| • Post pre-pregging operation; cutting, stitching, layup | • Mid term | • I lead, NL, U | • Equipment and expertise, high-level funding |
| • Ovens with detection system for toxic gas, fire, break/catenary; will help to detect these things before they get out of control | • Mid term | • NL lead, G, I | • Equipment and expertise, high-level funding |
| • Reduced variability and labor due to cure cycles | • Mid term | • I lead, NL, U | • Equipment and expertise, high-level funding |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 1

### Table 1-6. Priority RD&D Need: Faster Automated Process & Technologies for Parts Production

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • Higher volume automated production | • Mid term | • U, I, NL | • Equipment<br>• High funding |
| • High volume wind blade production | • Near term | • I, G, NL | • Facilities and equipment<br>• High funding |
| • Pilot validation—low-volume vehicle | • Near term for hood/roof demo | • All | • Facilities/equipment<br>• Medium funding |
| • High-speed tape head use fiber & resin 10X current rate | • Near term | • I, NL | • Facilities/equipment<br>• Medium funding |
| • Carbon fiber and glass chop head + secondary process | • Near term | • NL, NGO, I, U | • Equipment<br>• Medium funding |
| • Process investigation (scrimp, MIT, zero injection pressure [ZIP]) | • Mid term | • All | • Equipment + tools<br>• High funding |
| • Materials fast cure methods | • Near term | • All | • Equipment + tools<br>• High funding |
| • Literature search | • <1 year | • All | • Low funding |

For explanations of the abbreviations in this table, please refer to the "Keys for Breakout Group Tables" on Page vii.

# 2. Technical Breakout Group #2

The development of a domestic, low-cost carbon fiber composite industry is a strategic national priority that could have significant impact on the energy use of various sectors of the U.S. economy. Industry has identified the top R&D needs required to achieve this, and is already working on them. For example, there are "killer" applications available today, such as energy storage systems, rollers in paper manufacturing, and electric transmission cables, where carbon fiber has not been able to establish itself because of lack of stability in pricing and availability. To solve this problem, it is most important to identify the best possible way to implement the top R&D priorities. A major initiative is needed to make all stakeholders work together on a focus group and organize a consortium.

### Major Findings, Caveats, and Key Issues

- Most of the top R&D needs identified are already being worked on today
- Must identify how to get these R&D priorities into production/implementation
- We are still very separated by applications. We need to work together on a focused group. We need a major initiative to put everybody together (consortia)
- We recognize that because of the energy implications to different sectors the development of a domestic carbon fiber composite industry is a strategic national priority
- We recognize that Japan has stepped up to join the automotive industry and carbon fiber manufacturers to reduce costs
- "Killer" applications are available today (i.e., energy storage system, rollers in paper converting, electric transmission cables) but because of the lack of pricing stability and availability they haven't picked up yet
- Lowest cost doesn't only mean lowest price, it involves the total product delivered cost

There is a general agreement that a key R&D needed to advance low-cost carbon fiber composites is to accelerate the implementation of alternative low-cost precursors. Activities should focus on improving PO precursors, textile precursors, and lignin precursors. Long-term activities include increasing production of lignin to pilot-scale levels. Another key R&D need is to increase the production speed of carbonization. In the near term, this effort should focus on Microwave Assisted Plasma (MAP) processing and atmospheric plasma processing scale-up. In the long term, basic research of carbon properties at lower temperatures and/or shorter times is needed.

Increasing the speed of stabilization is another R&D priority. Key R&D activities needed to accomplish this include improvements in plasma-assisted stabilization, alternative precursor chemistries, decreasing fiber diameter, and upper-limit oven size optimization. Long-term activities include the use of ultraviolet (UV) energy and pressure assistance.

Another important R&D need is to reduce manufacturing recycle time. In the near term, this effort should focus on planning, resin development, and tooling. In the longer term, R&D should focus on improving work flow and joining methods.

There are different R&D approaches that could be implemented to accelerate the development of low-cost carbon fiber composites:

1) The establishment of a "demonstration facility" where equipment and staff could be available to enable researchers and developers to work more efficiently on their products.

2) The creation of vertically integrated teams, a “systems” approach, where a team includes a representative of expertise at each step along the way, from fiber precursor to finished composite part.
3) The use of “horizontally integrated” teams, which would focus on all aspects of one step in the entire system, precursors, for example, or matrix resins.

A demonstration facility would reduce risk by allowing access to capital equipment and resources, while protecting intellectual property (IP). A major advantage of this approach is the access to comparative information across various competing technologies and processes. Potential disadvantages to this approach include the concentration of talent in fiber spinning and conversion and the tendency for a “silo” mentality. Demonstration facilities have no capabilities for pilot-scale production and can become underutilized over time. It may also be difficult to obtain long-term funding commitment for the facilities.

A vertically integrated system approach involves a team that represents all of the steps in the production of low-cost carbon fiber composites. The approach starts with the end product in mind and encourages collaboration for all stakeholders. It allows for information sharing, develops opportunities for potential new markets, and protects IP. The two main disadvantages of this approach include the risk of having a minor impact across a broad industry category and that it may only affect the parties involved without guaranteeing scale-up.

The horizontally integrated team focuses on a single, key technology. It allows for IP protection and reduces risk. At the same time, this approach may have results that are too limited to reach critical mass.

A somewhat different, fourth approach would be a two-phase approach to rapidly scale-up low-cost carbon fiber production. Phase I would focus on pilot-scale production and would target the validation

### Demonstration Facility

**Advantages**
- Risk mitigation
- Resource sharing
- Access to capital equipment
- IP protection
- Access to support analytical characterization
- Availability of intellectual capital
- Allows for comparability between competing approaches

**Disadvantages**
- Concentration of talent in one place
- Can become underutilized over time
- No capabilities for pilot-scale production
- Hard to get long-term funding for the center
- Tendency to silo

### Vertically Integrated

**Advantages**
- Starts with the end product in mind
- Encourages collaboration for all stakeholders
- Information sharing
- Develops opportunities for potential new markets
- Helps protect IP

**Disadvantages**
- It only affects the parties involved and doesn’t necessarily guarantee scale up
- Risk of having minor impact across a broad industry

### Horizontally Integrated

**Advantages**
- Focuses on key technologies
- Secures IP
- Lower risk

**Disadvantages**
- It is incremental and may not reach critical mass
- Too status quo

and verification of emerging technologies. It must include a highly modular facility, incorporate existing and emerging technologies, and produce a substantial amount of carbon fiber. Phase II would focus on scale-up to full production. It would target the application of the technologies into various end products (e.g., wind, automotive, aerospace, etc.). This phase would include the capability to build a two million pound line subsidized by the Federal Government and supported by key partners of the industry.

### Two-Phase Production Approach for Rapid Scale-up

**Advantages**

- Allows for scale-up
- Helps mitigate risk
- Breakthrough potential, involves industry in moving towards domestic large-scale manufacturing, utilizing emerging technologies
- Validates and quantifies cost advantages

**Disadvantages**

- High risk and high capital and requires commitment from all parties
- Must be flexible to handle the different applications (must be a very big plant)
- Must be handled in a way so it doesn't threaten the carbon fiber industry
- Uncertainty if fiber companies would be interested in it
- IP protection must be handled very carefully

This approach has breakthrough potential because it allows for scale-up and helps users mitigate risk, while helping industry achieve large-scale production using emerging technologies. This is a capital-intensive approach that requires not only the development of a big facility capable of handling various applications, but it also involves commitment from everyone involved. Because this approach could present a threat to the carbon fiber producing companies, their participation is questionable.


Workshop participants consider key technical issues for low-cost carbon fiber composites during the breakout sessions.

## TABLE 2-1. TECHNICAL BREAKOUT # 2 PARTICIPANTS

| NAME | ORGANIZATION |
|---|---|
| Mohamed Abdallah | MGA- Advanced Composites & Engineering |
| Thomas Ashwill | Sandia National Laboratories |
| Steven Baldini<br>(Breakout Group Reporter) | Zoltek |
| Alain Bergeron | Kruger Wayagamack Ing |
| Jim deVries | Ford Motor Company |
| Takao Hayashi | Nissan Technical Center, North America |
| Ben Lemmons | American Starlinger Sahm |
| Stephen Nolet | TPI Composites |
| Robert Norris | ORNL |
| Rogelio Sullivan | North Carolina State University |
| Hubertus Thomeer | Schlumberger |
| Nikhil Verghese | Dow Chemical Company |
| Matthew Weisenberger | University of Kentucky |
| Dick Ziegler | Sentech |
| Mauricio Justiniano (Facilitator) | Energetics Incorporated |

## Technical Breakout 2

### Table 2-2. What Are the RD&D Needs Required to Lower Costs of Carbon Fiber Reinforced Composites?

| Composite Part Manufacturing | Design Engineering | Precursors | Carbon Fiber Production |
|---|---|---|---|
| • Reduction of manufacturing cycle time<br>◆◆◆◆◆<br>• Material testing of carbon/glass hybrids<br>◆◆<br>• High-speed fiber placement >100 Kg/hr<br>◆<br>• Introducing carbon fiber composites into high-volume markets<br>• Better/faster infusion processes<br>• Product form diversity<br>• Low-cost composite manufacturing methods automated composite manufacturing technology<br>• Better materials compatibility understanding<br>• Lower energy process for parts | • Targeted applications (focus)<br>◆◆<br>• Effects of defects – characterization<br>◆◆<br>• Integration methods with conventional systems<br>◆◆<br>• Parts integration idea by designer<br>• Improve engineering (finite element analysis [FEA]) of composites—confidence building<br>• Fastening/bonding technology improvement for cost reduction<br>• Repairability of structures<br>• Address repairability—total lifetime of part<br>• Improve recycling processes | • Accelerate the implementation of alternative low-cost precursor<br>◆◆◆◆◆◆◆◆<br>• Develop improved lignin precursors<br>◆◆◆<br>• New low-cost precursor materials<br>◆◆◆<br>• Textile precursors<br>◆◆◆<br>• Other spinning technologies<br>◆◆<br>• Reduce cost/need for high-yield precursors<br>◆ | • Increased production speed—carbonization<br>◆◆◆◆◆◆◆<br>• Faster stabilization<br>◆◆◆◆◆◆<br>• Take a systems approach (processing, chemistry of resins, tooling, etc.)<br>◆◆◆<br>• Lower cost capital equipment<br>◆◆◆<br>• Improve infusion manufacturing process to allow easier carbon handling to minimize waviness<br>◆◆<br>• Ability to upsize and downsize with little effect on price<br>◆◆<br>• Reducing/integrating production steps (spooling vs. weaving)<br>◆◆<br>• Lower energy process for fibers<br>◆◆<br>• Increase product line-speed<br>◆◆<br>• Standardization of materials—carbon fiber properties<br>◆<br>• Carbon fiber form flexibility (tow sizes, sizing, spooling technologies)<br>• Lower cost inspection and quality assurance (QA) methods<br>• Resin and carbon fiber material cost reduction keeping quality and performance<br>• Better translation of mechanical properties with vinyl ester (VE) and polyester<br>• Develop sizing for chopped fiber manufacturing processes |

# Technical Breakout 2

## TABLE 2-3. PRIORITY RD&D NEED: ACCELERATE THE IMPLEMENTATION OF ALTERNATIVE LOW COST PRECURSOR

| KEY RD&D ACTIVITY | TIMEFRAME | PARTNERSHIP STRATEGIES | RESOURCE REQUIREMENTS |
|---|---|---|---|
| • Textile precursor (60%)<br>– Reduce coefficient of variance (strength 300) | • Near term 2Q 2010 | • I (textile precursor suppliers) | • Low ~ $800K to wrap up lab studies |
| • PO precursor (35%)<br>– procure/develop low denier linear low density polyethylene (LLDPE)/PO <12 µm fiber<br>– Semi-continuous stabilization | • 1Q<br>• Near term 1 year | • I, NL<br>• NL | • Low funding<br>• Medium funding |
| • Lignin (<30%)<br>– Precursor composition/additives<br>– Accelerated stabilization | • Near term<br>• Near term | • I, NL<br>• I, NL | • Medium funding<br>• Medium funding |
| • Production (graduate to pilot scale)<br>– Textile<br>– PO<br>– Lignin | • Mid term<br>• Mid term<br>• Long term | • I<br>• I, NL<br>• I, NL | • Ultra high funding (2013) |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 2

### TABLE 2-4. PRIORITY RD&D NEED: INCREASING PRODUCTION SPEED-CARBONIZATION

| KEY RD&D ACTIVITY | TIMEFRAME | PARTNERSHIP STRATEGIES | RESOURCE REQUIREMENTS |
|---|---|---|---|
| • MAP processing scale-up | • Near term | • G, NL, I | • Medium-High funding |
| • Atmospheric plasma feasibility determination | • Mid term | • G, NL, U, I | • High funding |
| • Atmospheric plasma scale-up | • Mid term | • G, NL, I | • High funding |
| • Energy scavenging methods study for existing technology (lower cost, not necessarily faster) | • Near term | • I, G, NL | • Medium funding |
| • Basic research on carbon properties at lower temperatures and/or shorter times | • Long term | • U, G, NL | • Medium funding |

For explanations of the abbreviations in this table, please refer to the "Keys for Breakout Group Tables" on Page vii.

## Table 2-5. Priority RD&D Need: Faster Stabilization

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • Plasma-assisted stabilization<br>– Optimize res time<br>– Scale up | • Mid term | • I, G, NL, U | • High funding |
| • Alternative precursor chemistry<br>– Additives co-polymers | • Long term | • U, NL, G | • Medium funding |
| • Decrease fiber diameter (filament size optimization) | • Near term | • I, U, NL, G | • Low funding |
| • Upper-limit oven size optimization | • Near term | • I, NL, G | • Medium funding |
| • Alt. energy/UV | • Long term | • I, G, NL, U | • High funding |
| • Pressure-assisted stabilization | • Long term | • I, G, NL, U | • High funding |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 2

### TABLE 2-6. PRIORITY RD&D NEED: REDUCTION OF MANUFACTURING CYCLE TIME

| KEY RD&D ACTIVITY | TIMEFRAME | PARTNERSHIP STRATEGIES | RESOURCE REQUIREMENTS |
|---|---|---|---|
| • Plan<br>– Industry target part definition<br>– Goal setting | • 2–3 months | • Material supply chain<br>• I, NL | • People, time (data) |
| • Resin development<br>– Curing dynamics<br>– Viscosity<br>– Interface | • 3 years | • Chem. Comp<br>• I, U | • |
| • Molding/tooling<br>– Preform<br>– Fabric forming | • Near term<br>• 2 years | • I, U | • Facilities – High<br>• Equipment – High<br>• $ – High |
| • Work flow<br>– Preforms<br>– Flow balance<br>– Subassemblies<br>– Material transfer | • 3-years | • I, U, NL | • Low |
| • Joining methods<br>– Local heating<br>– Mechanical<br>– Adhesives<br>– Weaving technology<br>– Product form | • 3 years | • I, U testing, NL testing<br>• Industry dependent | • Facilities – Medium<br>• Equipment – Medium<br>• $ – Medium |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 2

### Table 2-7. What Are the Potential Approaches that Can Be Implemented to Address the Priority Needs?

| Vertical Integrated Team (System) | Focus on Single Aspect (Horizontal) | Demonstration Facility | Two-Phase Approach to Rapidly Scale-Up Low-Cost Carbon Fiber Production |
|---|---|---|---|
| <u>Costs</u><br>• High<br><br><u>Advantages</u><br>• Starts with the end product in mind<br>• Encourages collaboration for all stakeholders<br>• Information sharing<br>• Develops opportunities for potential new markets<br>• Helps protect IP<br><br><u>Disadvantages</u><br>• It only affects the parties involved and doesn't necessarily guarantee scale up<br>• Risk of having minor impact across a broad industry | <u>Costs</u><br>• Medium<br><br><u>Advantages</u><br>• Focuses on key technologies<br>• Secures IP<br>• Lower risk<br><br><u>Disadvantages</u><br>• It is incremental and may not reach critical mass<br>• Too status quo | <u>Costs</u><br>• High<br><br><u>Advantages</u><br>• Risk mitigation<br>• Research that doesn't work on an academic timescale<br>• Resource sharing<br>• Access to capital equipment<br>• Capability to protect your IP<br>• Access to support analytical characterization at ORNL<br>• Availability of intellectual capital<br>• Allows for comparability between competing approaches<br><br><u>Disadvantages</u><br>• Concentration of talent in fiber spinning and conversion<br>• Become underutilized over time<br>• Citizenship requirements<br>• No capabilities for pilot-scale production<br>• Hard to get long-term funding commitment for the center<br>• Tendency to silo | <u>Costs</u><br>• High<br><br><u>Aspects</u><br>• Phase I – Pilot Scale Production: would focus on validation and verification of the emerging technologies. Must be a highly modular facility, incorporate existing and ORNL's emerging technologies, and produce a substantial amount of carbon fiber.<br>• Phase II – Scale-up to Full Production: would focus on the application of the technologies into various end products (e.g., wind, automotive, aerospace, etc.). Build 2 million pound line subsidized by the Federal Government, supported by key partners of the industry.<br><br><u>Advantages</u><br>• Allows for scale-up<br>• Helps mitigate risk<br>• Breakthrough potential, involves industry in moving towards domestic large-scale manufacturing, utilizing emerging technologies<br>• Validates and quantifies cost advantages |

| VERTICAL INTEGRATED TEAM (SYSTEM) | FOCUS ON SINGLE ASPECT (HORIZONTAL) | DEMONSTRATION FACILITY | TWO-PHASE APPROACH TO RAPIDLY SCALE-UP LOW-COST CARBON FIBER PRODUCTION |
|---|---|---|---|
| | | | <u>Disadvantages</u><br>• High risk and high capital and requires commitment from all parties<br>• Must be flexible to handle the different applications (must be a very big plant)<br>• Must be handled in a way so it doesn't threaten the carbon fiber industry<br>• Uncertainty if fiber companies would be interested in it<br>• IP protection must be handled very carefully |

# 3. Technical Breakout Group #3

The best approach to developing an RD&D plan for low-cost carbon fiber composites that are suitable for diverse energy-related applications is to use a systems approach. Currently, the various steps (precursor identification and development, fiber processing/manufacturing, fiber surface treatment and interfacing for composite manufacture, development of resins for the matrix constituent, and composite manufacturing) are too often treated separately, with little attempted coordination between steps. With a systems approach, all steps of the RD&D process are considered together, from identifying and developing the fiber precursor to producing finished components.

There are several issues standing in the way of producing low-cost carbon fiber composite components at every point along the development pathway. For example, if inexpensive precursors are used to make the fiber, the fibers are difficult to process. Also, if the composite matrix is made with a relatively inexpensive resin, expensive fiber surface treatment and fiber sizing is necessary. A systems approach is the best method to address these and other issues in order to lower costs of the carbon fiber as well as other materials along the pathway.

It is generally agreed that RD&D of fiber precursors is the vital step in developing low-cost carbon fiber composites. In order to accomplish this, fiber attributes and requirements must be first identified and then existing precursors that might successfully be made into such fibers must be identified. While fiber production from these precursors is being tested at pilot scale, research should continue to develop new precursors, both natural and synthetic. As these are developed and tested, the most promising should be tested at pilot scale as well. Finally, successful precursor/fibers should be scaled up and eventually commercialized.

### Major Findings, Caveats, Key Issues

- A systems approach is needed
  - There are multiple steps in the process
  - Currently they are being treated individually
- We need to define the goals, fiber requirements (cost, properties, volume, fiber forms) that are application dependent
- Approach needs to be flexible, sophisticated and inexpensive
- Need to look at continuous fiber, but also chopped and milled fiber
- Today's carbon fiber industry would be challenged to respond to the need for low-cost high volume carbon fiber
- Current low-cost carbon fiber is difficult to process
- Surface treatment and sizing are critical to enable use with lower-cost resins
- We have to move to a greener chemistry

A criticism of carbon fiber processing today is the fact that it cannot be done in high volume. Currently, carbon fiber manufacture is limited to 10–20 feet per minute, while analogous glass fiber can be manufactured at about two orders of magnitude faster. A priority requirement to developing lower cost carbon fiber composites is to find ways of increasing the volume of carbon fiber manufactured to meet the demand of diverse industries. A pilot plant that can make carbon fiber (much like that discussed above) by current methods should be established as a starting point and should then be optimized. Optimization should include the oxidizing (stabilizing) equipment, low- and high-temperature carbonization furnace designs, automation techniques, winding technology, and speed. Optimized process systems should be tested with PAN and with new low-cost, high-volume precursors.

Another area that must be optimized to develop low-cost carbon fiber composite is the interface between the carbon fiber and its resin matrix. Areas of activity should include optimizing parameters such as limiting oxygen index (LOI), wettability, reactivity, and surface energy. In addition, it is necessary to identify and develop a low-cost resin for the composite matrix.

In the composite manufacturing area, rapid cycle is a very important RD&D need. Areas where the manufacturing step can be improved include advanced, low-cost fiber placement methodologies including the prepreg approach and the appropriate chemistry for the matrix resin. In addition, there is a need for R&D on appropriate manufacturing tooling, likely involving an integrated approach. Surface requirements and the nature of the winding process are also parts of this. Finally, low-cost composite manufacturing methods such as resin-transfer molding (RTM), structural reaction injection molding (SRIM), and sheet molding should be considered as well.

The overall process can be enhanced by the use of modeling to both speed up and focus various steps of the process. For instance, modeling could be used to design the chemistry of carbon fiber precursors that would be low cost and of optimum quality for the required market. Also, predictive models could be made for preforms for fast cycle composites. This might focus on "spray-up" preforms and long fiber flow compression molding.

Several approaches could be considered to determine the method to implement the RD&D needed to address low-cost carbon fiber composites. One approach could be the establishment of a "demonstration facility" where equipment and staff could be available to enable researchers and developers to work more efficiently on their products. A second approach involves the establishment of vertically integrated teams, a "systems" approach, in which a team included a representative of expertise of each step along the way—from fiber precursor to finished composite part. A third approach would be a "horizontally integrated" team, which would focus on all aspects of one step in the entire system - precursors, for instance, or matrix resins.

A demonstration facility could be a fully integrated site, fully accessible to all, but would be unbiased toward any particular user. It is visualized as being adaptive to most precursors and processes, as possibly having a centralized database, and as providing low-cost manufacturing capabilities. Such a facility could invite many stakeholder industries to participate and to share information where appropriate. One type of demonstration facility could specialize in modeling. This particular facility could conceivably be a virtual facility.

Demonstration facilities as an implementation approach would minimize industry risk while accelerating development at a relatively low cost. It would have the ability to provide materials (fibers, composites) in sufficient quantity to allow customer evaluation. A successful demonstration facility would create its own momentum and synergy. However, despite its

### Demonstration Facility

**Advantages**

- Mitigates risk and lowers cost to industry
- Facilitates the development and commercialization of low cost carbon fiber composites
- Enables U.S. workforce development and technological and manufacturing leadership
- Provides locus and forum for networking and exchange of ideas

**Disadvantages**

- Requires a large capital investment
- IP management must be skillfully crafted
- Management is key

advantages, a flexible, "do all," demonstration facility may be difficult to create. Drawbacks would also include issues of security, IP, control, location, and ease of access.

A vertically integrated system approach would involve a team that represented all of the steps involved toward making low-cost carbon fiber composites. It would likely have a central database, perhaps managed by a trade association, and could represent one or several technology streams.

The vertically integrated system would be advantageous in that it would connect the supply chain to the market, forcing an identification of requirements directly from the customer. It would thus speed commercialization, and would also increase efficiency and disperse the risk among its constituents. A disadvantage of this approach is that it is costly, requiring industry investment at a level that may be difficult to obtain. Another disadvantage is that vertically integrated teams may not communicate with one another.

### Vertically Integrated Approach

**Advantages**

- Connections from supply chain to market
- Forces definition of needs and requirements (voice of the customer)
- Enables faster commercialization
- Reduces and distributes the risk
- Improved efficiencies
- Integrates U.S.-based supply chain

**Disadvantages**

- Requires significant coordination (e.g., budget, IP, time)
- Requires staying in pre-competitive space
- Requires a paradigm shift in thinking – this is not the "normal way of doing things"

The third approach, the horizontally integrated team focused on a single system step, has some value in that it would provide a great level of detail for that particular step, thereby increasing the chances of success for that step. It might be a viable approach where results are needed for a single critical issue, if used in conjunction with an adjacent systems approach. However, the horizontal approach in itself might ignore other factors - especially ones that are system-related. It is a selective, isolated approach that may be difficult to manage.

### Horizontally Integrated Approach (in a single step)

**Advantages**

- Provides in-depth focus if needed (may complement elements of a systems approach)
- Increase the chances of success on that one item
- Viable option for single organization with limited resources

**Disadvantages**

- Loss of perspective
- Distraction from systems approach
- Promotes "silo" mentality

### TABLE 3-1. TECHNICAL BREAKOUT # 3 PARTICIPANTS

| NAME | ORGANIZATION |
|---|---|
| Frederick Baker | ORNL |
| Lionel Batty<br>(Breakout Group Reporter) | GrafTech International |
| Paul Bissett | Weyerhaeuser |
| Robert Blackmon | Harper International |
| Mike Cretella | PPG |
| Eric deNijs | Cosma Engineering |
| Scott Finn | General Electric |
| Joseph Hayes | American Kynol Inc. |
| Hamid Kia | General Motors |
| James Kolb | American Chemistry Council |
| Jeffrey Robbins | Meridian Automotive Systems |
| Vikram Singh | Varian Semiconductor Equipment Associates |
| Karla Strong | U.S. Air Force |
| Edward Zenk | Navistar Inc. |
| Jose Zayas | Sandia National Laboratories |
| Ed Skolnik (Facilitator) | Energetics Incorporated |

## Technical Breakout 3

### Table 3-2. What Are the RD&D Needs Required to Lower Costs of Carbon Fiber Reinforced Composites?

| Precursors | Fiber Processing | Surface Treatment Sizing Interface | Resins | Composite Manufacturing | Other |
|---|---|---|---|---|---|
| • Develop cost-effective, energy-efficient precursors to make fibers that meet market needs ◆◆◆◆◆◆◆◆◆◆<br>– Thermoset precursor<br>– Lignin precursor<br>– Other precursors<br>• Grow trees faster ◆<br>– Increase lignin content (bio-engineering)<br>– Cut trees down faster! | • Ways to increase high-volume carbon fiber manufacturing to meet demand and diverse industries ◆◆◆◆◆◆◆◆◆<br>– Current production speed(s) are 10–20 ft/min<br>• Simplify processing steps to fewer and continuous ◆◆◆◆◆<br>– Eliminate furnace (plasma)<br>– Eliminate stabilization (thermoset)<br>• Cost-efficient processing ◆◆<br>– Energy<br>– Time<br>– Unit operations<br>• More readily produced carbon fiber with higher carbon yield | • Optimize interface between fiber and resin ◆◆◆◆◆◆◆◆◆<br>– Fiber sizing R&D<br>– Surface chemistry of fiber | • Low-cost resin for composite matrix ◆◆◆◆◆◆<br>– Infusion resins<br>– Lignin resin<br>– Etc. | • Fast cycle composite manufacturing ◆◆◆◆◆◆◆◆<br>• Low-cost fiber placement ◆◆◆<br>– Small complex shapes<br>– Automation<br>• Hybrid composite designs to optimize carbon cost and performance ◆◆◆<br>• In-line monitoring and inspection of parts manufacturing processes | • Modeling ◆◆◆◆◆◆◆◆◆◆<br>– Reduce qualifications cost<br>– Fiber process and chemical modeling<br>– Component manufacturing<br>– Predictive engineering<br>– Minimum Property of fiber–carbon content<br>• Demonstration Facilities for carbon fiber development (heat treatment, part forming, etc.) ◆◆<br>• Knowledge base ◆◆<br>– Publicly available processing know-how<br>– Plasma and surface chemistry database<br>– Design guidelines<br>• Broaden carbon fiber supply base ◆<br>• Industrially available carbon fiber pilot line<br>• More demonstration/ transition projects<br>• Fiber packaging (why 10 kg bobbins? crimping, splitting, shipping) |

## Technical Breakout 3

### Table 3-3. Priority RD&D Need: Develop Cost Effective, Energy Efficient, Precursor to Make Fibers that Meet Market Needs

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • Identify needed attributes and requirements of fibers for existing and potential markets | • ~6 months | • I lead, NGO | • Expertise<br>• Low funding |
| • Identify existing precursors and likely fit with needs in above activity | • ~6 months | • I lead, NL, U | • Expertise<br>• Low funding |
| • Pilot plant fiber production - flexibility so it can handle multiple precursors | • ~1–2 years | • NL lead, I, U, NGO | • Facilities<br>• Equipment<br>• Expertise<br>• High funding |
| • Identify potential new precursors and likely fit with needs in first activity<br>– Synthetic<br>– Natural | • ~1 year | • I, NL, U, G | • Expertise<br>• Medium funding |
| • Develop new precursor (take to Pilot Plant) | • Mid term | • I, NL, U, G | • Facilities<br>• Equipment<br>• Expertise<br>• High funding |
| • Scale up and commercialize | • ~2 years | • I | • Facilities<br>• Equipment<br>• Expertise<br>• High funding |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 3

### Table 3-4. Priority RD&D Need: Modeling

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements |
| --- | --- | --- | --- |
| • Model of carbon fiber manufacturing to chemically design precursors for optimum cost/quality of requirement | • Mid term | • U, NL, I | • Carbon fiber expertise<br>• Modeling expertise<br>• Medium-high funding<br>• Computers/software |
| • Predictive models for carbon fiber preforms of fast cycle composites. Focus is with spray up of a fiber preform and long fiber flow like compression mold. Does not include lay up and preform without flow. | • Near term | • U, I, NL | • Computers/software<br>• Modeling expertise<br>• Medium funding<br>• Fast cycle processing expertise |

For explanations of the abbreviations in this table, please refer to the "Keys for Breakout Group Tables" on Page vii.

## Technical Breakout 3

### Table 3-5. Priority RD&D Need: Ways to Increase High-Volume Fiber Manufacturing to Meet Demand and Diverse Industries

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • Establish carbon fiber pilot line based on current state-of-art standards | • 2–3 years | • G,NL,I<br>• I = (material and equip manufacturers)<br>• Government is primary funding source | • Physical assets have capital expense; dollars, donation, physical location, operating structure<br>• High funding $6–$10M |
| • Oxidation oven equipment optimization (design, residence time [RT], packing density) | • Mid term | • I, NGO, NL* | • As directed by industry<br>• PAN feed (known, existing)<br>• Expertise<br>• Medium funding; industry bears cost |
| • Low Temp furnace, High Temp furnace design optimization | • Mid term | • I, NGO, NL* | • PAN (known existing)<br>• Expertise<br>• Equipment<br>• Medium-high funding; industry bears cost |
| • Automation techniques<br>• Winding technology<br>• Creel technology<br>• Speed optimization | • Mid term | • I, NGO, NL* | • PAN (known existing)<br>• Expertise<br>• Equipment<br>• Low funding; industry bears cost |
| • Precursor: demonstrate that low-cost, high-volume precursor candidates can be converted.<br>• Generate sufficient samples for downstream industry testing | • Mid term + longer | • I, NGO, NL* | • Fundamental recipe needed first: PAN (new candidate)<br>• Expertise<br>• Equipment<br>• Medium-high funding; industry bears cost |

* Initial government or national laboratory establishes operating company whose costs eventually are carried by consortium members but acts as an umbrella to maintain neutrality.

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 3

### Table 3-6. Priority RD&D Need: Fast Cycle Composite Manufacturing

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • Fiber placement<br>– Prepreg approach<br>– Programmable Powdered Preform Process ($P_4$)<br>– Other novel methodology fiber placement | • Auto: Mid term<br>• Energy: Mid term | • I, NL, U, G | • Expertise<br>• Equipment<br>• Funding: high |
| • Resin chemistry<br>– Cure times<br>– Properties (cost mechanical)<br>– Tolerances | • Auto: Near term –>Long-term RD&D<br>• Energy: Near term –>Long-term RD&D | • I, NL, U, G | • Expertise<br>• Facilities<br>• Funding: high |
| Focus on U.S. jobs and manufacturing technology<br>• Tooling R&D<br>– Integrated approach<br>– Surface requirements<br>– Finishing (wind) | • Near term –> Long term RD&D | • I , G | • Expertise<br>• Facilities<br>• Funding: high |
| • Enhancing manufacturing<br>– RTM<br>– Prepreg manufacturers<br>– SMC<br>– SRIM<br>– Automation | • Ongoing | • NL, I, U, G | • Expertise<br>• Facilities<br>• Equipment<br>• Funding: high |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 3

### Table 3-7. Priority RD&D Need: Optimize Interface Between Fiber and Resin

| Key RD&D Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • LOI – optimize | • Near term | • I, U | • Facilities<br>• Equipment<br>• Low funds |
| • Wettable | • Near term | • U | • Facilities<br>• Equipment<br>• Low funds |
| • Surface Energy Δ | • Mid term | • NL, U | • Equipment<br>• Medium funds |
| • Cross link (reactivity) | • Mid term | • I, U | • Expertise<br>• Medium funds |
| • Surface treatment | • Mid term | • I, U | • Facilities<br>• Medium funds |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Technical Breakout 3

### Table 3-8. What Are the Potential Approaches that Can Be Implemented to Address the Priority Needs?

| Vertical Integrated Team (System) | Focus on Single Aspect (Horiz.) | Demonstration Facility | |
|---|---|---|---|
| <u>Aspects</u><br>• Develop roadmap—industry to facilitate new ideas and wider participation<br>• Central database, association managed<br>• Will there be one regime of technology, or several? Need to avoid pre-conception, pre-commitment to specific technology stream.<br><br><u>Advantages</u><br>• Addresses the overall process<br>• Gets more people in<br>• Communication<br>• Promotes clear definition of end-use requirements<br><br><u>Disadvantages</u><br>• Most time consuming and costly<br>• "Levels the playing field"<br>• May inhibit communication between teams<br>• Will require investment by industry that may be difficult to achieve | <u>Advantages</u><br>• Great level of detail<br>• Focused look<br>• Prioritizes industry needs<br><br><u>Disadvantages</u><br>• Might miss other factors<br>• May ignore other issues<br>• Horizontal approach is difficult to manage and lead … not comprehensive. It is selective, focused, ear-marked<br>• Isolation from upstream capabilities and downstream needs | <u>Aspects</u><br>• "Neutral" site and staff<br>• Freely accessible<br>• Fully integrated<br>• Highly adaptive<br>  – Precursors<br>  – Advanced process<br>• Centralized database<br>• Link with resin<br>• Manufacture for low cost<br>• Compatible resins<br>• Invite many industries to the line to encourage growth and new manufacturers<br>• Virtual demonstration facility for developing modeling managed by one entity (university?)<br>• Vertical exchange of information, terminology, and insights is more important than machines<br>• Needs to include knowledge expertise base<br><br><u>Advantages</u><br>• New equipment<br>• No perceived bias<br>• Minimizes industry risk<br>• Accelerate development and commercialization<br>• Provides an opportunity to evaluate the innovation without the economic implication<br>  – Consistency in staff<br>  – World-class expertise<br>• Develops manufacturing technology | <u>Advantages</u> (cont.)<br>• Could publish data, guidebooks, and other information needed for successful applications<br>• Would provide fiber conversion capacity necessary for customer evaluation and product development<br>• Demonstration facility that includes carbon fiber processing and composite manufacturing will help vertical integration<br>• Demonstration facility will produce empirical data needed for modeling or model verification<br>• Low-cost option for industry to pilot development<br>• Demonstration Facilities tend to create their own momentum and synergy, if successful. Strong management!<br><br><u>Disadvantages</u><br>• Security<br>• Politics (if government site)<br>  – Science/tech. takes a back seat<br>  – Lack of continuity of funding<br>  – Business management by government<br>• International Trafficking in Arms Regulations (ITAR)/export control<br>• Sensitive countries: India and China emerging industry leaders<br>• Difficult/costly to develop a flexible framework to meet industry needs and direction<br>• Stays a lab environment |

| VERTICAL INTEGRATED TEAM (SYSTEM) | FOCUS ON SINGLE ASPECT (HORIZ.) | DEMONSTRATION FACILITY | |
|---|---|---|---|
| | | in U.S. - Jobs<br>• A lab environment | • IP/proprietary information sensitivity<br>• Issues of location, access, IP, scope, control |

# 4. Business Breakout Group

The availability of low-cost carbon fiber composites assumes the realization of a significant reduction in cost for associated materials, technologies, and manufacturing processes. As is the case with many developing technologies, costs must come down in order for a viable market to be created in which downstream buyers are not prohibited based on price.

Just as many factors contribute to the current high cost of carbon fiber composites, there are a number of fronts on which costs can be lowered. For one, the current value chain must become "leaner." Currently, too many points along the value chain are high in cost, which contributes to an expensive end product that is unattractive to would-be buyers. A lean value chain would better enable a favorable return on investment (ROI), in part due to the high value - not cost - of the end product.

Manufacturing is a significant point along the value chain, and current processes do not allow for the volume of production that is commensurate with lower cost. Thus, high-volume, large-scale, low-cost manufacturing processes represent a key goal for carbon fiber composites.

**Major Findings, Caveats, Key Issues**

- Cost and ROI are significant concerns. The "leaning" of the value chain can play a large role in reducing cost and increasing ROI. In addition, new technologies could be implemented to provide low-cost, high-volume manufacturing processes.
- Reduction in risk on two fronts (investment, end use product) is important for the development of low-cost carbon fiber; this may be achieved via a number of means, including incentives and reduction of regulatory barriers.
- Over-specification is problematic as it drives up cost.
- The development of technical standards is a key market driver.

The improvement of manufacturing technology and the "leaning" of the value chain can be achieved through a better understanding of the value chain itself, enabled by a "roadmapping" of the carbon fiber value chain. Then, armed with a greater understanding of the value chain, national labs in partnership with industry should identify key technologies and processes as well as establish goals for cost, quality, and performance by market segment. This may be based on a "Tech Process Improvement Plan" that is developed by industry. Finally, a government funding program, though estimated to be on the order of $100 million, could be a long-term solution for improving manufacturing technology and achieving a leaner value chain.

At the beginning of the value chain, the availability of raw materials is neither constant nor predictable. A diversity of materials is needed to ensure greater availability and the stabilization of price fluctuations that are currently associated with materials. The issue of material availability can be mitigated through forecast-able demand, with partnership strategies that may include supply agreements, joint ventures, and vertical integration. Beyond this, a financial justification is necessary, and regulations and incentives may play a supporting role.

Finally, a "breakthrough" technology may become available that allows for significant cost reduction. Specific cost-reducing breakthrough technologies that could be developed might include a low-cost lignin or PO precursor, a microwave-assisted carbonization and composite cure, hybrid carbon/glass fiber systems, and a system that performs acceptably using low-cost epoxies. Further, an innovative manufacturing process that enables high-volume production is necessary.

Risk is another issue that must be minimized before low-cost carbon fiber composites become a viable market. In particular, a number of regulatory "blocks" are seen as significant risk factors (and by many as unnecessary), including ITAR, Export Administration Regulations (EAR), and safety regulations. Another risky endeavor will be the first full-scale demonstration in expensive applications because whoever is first to attempt this will encounter a relatively high level of risk - which may be a deterrent. An evaluation of the current state of regulations is necessary, followed by a challenging of the regulations that are seen as deleterious to industry. A probabilistic analysis and design, though expensive, is a long-term activity that could be undertaken by universities and national laboratories.

There are a number of external elements that can have an effect on large-scale deployment for key applications. Perhaps the greatest of these is technical standards. In short, a higher degree of technical standards will result in lower cost. The cost of energy (oil, wind, etc.) is another factor that has implications for the carbon fiber composite market, in addition to social consciousness (i.e., with regard to global warming).

To address the need for technical standards, several developments need to take place, including the selection and establishment of a governing body, the establishment of a class of standards, and the qualification of test labs. These are near- to mid-term activities and should involve industry in partnership with national laboratories and possibly universities. Funding requirements for these activities should be relatively low, on the order of $1 million.

In the area of quality and performance, over-specification currently is an issue. For the carbon fiber composite market, many deliveries don't meet specifications. The challenges posed by over-specification can be overcome through the development of a global consortium, the development of common specifications for carbon fibers, and the merging of existing specifications into common specifications.

Standards can also apply to processes like manufacturing, and more standards in this area will ensure that costs are reduced through the use of like processes. Finally, the acceptance of material substitution for metals will encourage manufacturing scale-up.

There are three possible implementation approaches. The first approach is to stimulate private enterprise via a cost-share arrangement between government and industry, which can spread the risk between multiple entities, allowing for competitive solicitations, free enterprise, and for contributions from Small Business Research Funding opportunities (i.e., Small Business Innovation Research [SBIR]). It also allows foreign dollars to flow into the U.S. economy. Funding will likely need to be at a level that is adequate to encourage participation by industry.

### Government – Industry Cost Sharing Approach

**Advantages**

- Will allow call for proposals, can leverage SBIR, risks are "shared," can stimulate multiple companies, easier to uphold IP, will allow foreign companies to enter with investment $ in U.S. economy, allows for free enterprise to take course and for strategic partnerships to be developed

**Disadvantages**

- Private sector may not take advantage if inadequately funded

A second approach, the scale up and vertical integration of demonstration projects, has the potential to achieve desirable dollars per pound levels and volumes sufficient for development at a reasonable price. Additionally, there would be the possibility to learn from failures under this approach and to derive value-added products from biorefineries. A disadvantage of this approach is that these activities will be highly visible, and too many failures could hurt chances for market acceptance.

A third approach involves the development and deployment of advanced technology at specific points within the value stream. This horizontal approach can allow for a focus on points in the value chain with highest potential. Furthermore, this approach can leverage existing funding vehicles like Broad Agency Announcements (BAA) and Small Business Research Funding Opportunities. The disadvantages relate to the fact that the DOE is already working in this area, and that the process would take too long and be an administrative burden.

### Scale Up and Vertical Integration of Demonstration Projects

**Advantages**

- Achieve desirable $ per lb (tonnage), achieve volume sufficient for product development at a reasonable price, application to the end product, ability to learn from failures, derive value added products from biorefineries

**Disadvantages**

- Too many failures will taint market acceptance (too much visibility)

### Horizontally Integrated Approach

**Advantages**

- Allows for focus on points in the value chain with highest potential, mechanism is already in place for govt. to provide stimulus (BAA, SBIR)

**Disadvantages**

- DOE is already doing it, time consuming process (administrative burden)

## Business Breakout

### Table 4-1. Participants

| Name | Organization |
|---|---|
| Rashid Abdul | Gamesa Technology |
| Eliot Assimakopoulos | GE |
| Glenn Barefoot | Strongwell |
| William Clinkscales | Structural Composites Industries |
| Jose Miguel Contreiras | FISIPE |
| H.T. DelliColli | Lignol Innovations Inc. |
| John Gorog | Weyerhauser (retired) |
| Michael Keeler | Hendrickson |
| Gary Krause | Michigan Economic Development Corporation |
| Christopher Layton | Fi-Tech, Inc. |
| James Leslie | Advanced Composite Products and Technology Inc. |
| Rick Lowden | ODUSD (IP) |
| Michael Muser | Ingersoll Machine Tools |
| Peter Oswald | Toho Tenax America, Inc. |
| Mark Rivers (Breakout Group Reporter) | Despatch Industries |
| Billy Roeseler | Boeing |
| Balazs Tolnai | Kruger Inc. |
| Brad Spear (Facilitator) | Energetics Incorporated |

## Business Breakout

### Table 4-2. What Are the Market Issues and Challenges Associated with Large-Scale Deployment and Manufacturing Scale-up for Key Applications?

| Quality and Performance | Market Drivers | Risk | Cost and ROI |
|---|---|---|---|
| • Specifications! Lots of deliveries do not meet spec! Over specification?<br>◆◆◆◆◆◆◆◆◆<br>• Acceptance of material substitution for metals<br>◆◆◆◆<br>• Consistent quality<br>• Pultrusion! How do we get high quality from low-cost process?<br>• Standardization of process (current suppliers have their own technology) | • Standardization (tech standards)<br>◆◆◆◆◆◆◆◆<br>• Cost of energy, oil, wind<br>◆◆◆◆◆<br>• Social conscience, e.g., global warming<br>◆◆<br>– Carbon policy | • Regulatory blocks, safety, ITAR/EAR. Too many unnecessary regulations!<br>◆◆◆◆◆◆◆◆◆<br>• First full-scale demonstration in expensive applications like oil production. Who will try first? Who will be first?<br>◆◆◆◆<br>• Market Issues. Focused markets?<br>◆<br>– Prestige vs. commodity<br>• Market acceptance of replacement technologies or transition to novel applications (customer acceptance)<br>◆<br>• Convince internal risk management people it is worth the investment<br>• Government incentive<br>• Incentive! What are incentives for oil people to reduce mass of risers and tethers?<br>• How will we mitigate risk of breakage, leakage, storm damage – oil and wind? | • "Lean" the value chain<br>◆◆◆◆◆◆◆◆◆◆<br>• Lower cost<br>• Improving manufacturing technology<br>◆◆◆◆◆◆◆◆◆◆<br>– Volume and productivity restrictions due to manufacturing technology<br>– High volume, low cost manufacturing process<br>• Need for breakthrough technology to reduce cost<br>◆◆◆◆◆◆◆◆◆<br>• Material availability<br>◆◆◆◆◆◆◆◆<br>– Diversity to ensure material availability<br>– Less price fluctuations<br>• How do we justify the investment of a long development program in which we will not see a payoff for a long time?<br>• "Business Case" Investment! Who will make the multi-billion dollar investment to get risk out? Wind, oil industries<br>• Conversion<br>– Infrastructure<br>– Existing: write off's<br>– New: payback? |

## Table 4-3. Priority Market Issue Challenge: Standardization (Technical Standards)

| Key Deployment Scale-Up Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • Establish who is going to be the governing body | • Near term | • I | • Expertise<br>• Low-medium funding |
| • Establish class of standards | • Near term | • I, NL | • Expertise<br>• Low-medium funding |
| • Establish standards | • Mid term | • I, NL, U | • Expertise<br>• Facilities<br>• Equipment<br>• Low-medium funding |
| • Qualify test labs | • Mid-long term | • I, NL, U | • Expertise<br>• Low funding |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Business Breakout

### TABLE 4-4. PRIORITY MARKET ISSUE CHALLENGE: IMPROVE MANUFACTURING TECHNOLOGY AND LEAN THE VALUE CHAIN

| KEY DEPLOYMENT SCALE-UP ACTIVITY | TIMEFRAME | PARTNERSHIP STRATEGIES | RESOURCE REQUIREMENTS |
|---|---|---|---|
| • Road mapping carbon fiber value chain | • Near term | • NL | • Low funding |
| • Identify key technology/processes | • Near term | • NL, I | • Low funding |
| • Establishing goals—cost/quality/performance—by market segment | • Near term | • NL, I | • Low funding |
| • Developing tech process improvement plan | • Mid term | • I | • High funding |
| • Government funding program | • Long term | • G, I | • High – $100M |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Business Breakout

### TABLE 4-5. PRIORITY MARKET ISSUE CHALLENGE: REGULATORY BLOCKS

| KEY DEPLOYMENT SCALE-UP ACTIVITY | TIMEFRAME | PARTNERSHIP STRATEGIES | RESOURCE REQUIREMENTS |
|---|---|---|---|
| • Evaluate current state | • Near term | • I, G | • Low funding |
| • Challenge "bad" regulations | • Mid term | • I, G | • High funding |
| • Probabilistic analysis design | • Long term | • U, NL | • High funding |

For explanations of the abbreviations in this table, please refer to the "Keys for Breakout Group Tables" on Page vii.

## Business Breakout

### TABLE 4-6. PRIORITY MARKET ISSUE CHALLENGE: BREAKTHROUGH TECHNOLOGIES TO REDUCE COST

| KEY DEPLOYMENT SCALE-UP ACTIVITY | TIMEFRAME | PARTNERSHIP STRATEGIES | RESOURCE REQUIREMENTS |
|---|---|---|---|
| • Develop low cost lignin precursor or PO | • Near term | • I, NL | • Medium funding |
| • Develop microwave assisted carbonization and composite cure | • Near term | • I, NL | • High funding |
| • Develop system with acceptable performance using low cost epoxies or other low cost VEs | • Near term | • I, NL | • High funding |
| • Develop hybrid carbon/glass fiber systems | • Near term | • I, NL | • Med funding |
| • Innovative manufacturing processes to enable high volume production – chopped fiber, SMC, pultrusion | • Near term | • I | • High funding |
| • Scale-up natural fibers | | | |

For explanations of the abbreviations in this table, please refer to the "Keys for Breakout Group Tables" on Page vii.

## Business Breakout

### Table 4-7. Priority Market Issue Challenge: Material Availability

| Key Deployment Scale-Up Activity | Timeframe | Partnership Strategies | Resource Requirements |
|---|---|---|---|
| • Forecastable demand | • Mid term | • Supply agreements<br>• Joint ventures<br>• Vertical integration | • Facilities<br>• Equipment<br>• Low funding |
| • Financial justification | • Near term | • I | • Facilities<br>• Low funding |
| • Regulations and incentives | • Near term<br>• Mid term<br>• Long term | • G | • High funding |
| • Technology development | • Mid term<br>• Long term | • I, NL, U, G | • Expertise<br>• Facilities<br>• Equipment<br>• High funding |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

## Business Breakout

### TABLE 4-8. PRIORITY MARKET ISSUE CHALLENGE: SPECIFICATIONS

| KEY DEPLOYMENT SCALE-UP ACTIVITY | TIMEFRAME | PARTNERSHIP STRATEGIES | RESOURCE REQUIREMENTS |
|---|---|---|---|
| • Develop common spec for carbon fibers | • Near term | • I (fiber producers, end users, equipment suppliers), U | • High funding<br>• Expertise<br>• Facilities<br>• Equipment |
| • Development of a global consortium | • Near term | • I, G, U, NL, | • Low funding<br>• Expertise |
| • Merge existing specs into common specs | • Long term | • I | • High funding<br>• Expertise<br>• Facilities<br>• Equipment |

For explanations of the abbreviations in this table, please refer to the “Keys for Breakout Group Tables” on Page vii.

# 5. “Sound Bites”

There are plenty of low cost options out there - need to expand on these to other applications such as oil rigs and transmission lines

Would have liked to see more detail on composite conductors

There was not any mention of using carbon fiber for electric transmission and distribution lines

Not enough focus on applications

Very interesting, looking forward to next step and what is to come out of this conference

Excellent array of people gathered, wonderful collaborative effort trying to solve a common problem

There is precedent set out there for commodity contracts for materials, at least in automotive. We could do it for aluminum, magnesium, carbon fiber if it came to the right price and reliable supply.

Expectations have increased during this meeting

Would like future data about dollars per pound of carbon fiber also published with dollars per pound of end use application

There should be incentives for groups to get together and work on key issues

Need to get industries together to discuss an approach for more widespread use of carbon.
There are barriers: our fiber producers compete with each other; our auto companies compete with each other.

Was impressed with just how difficult the technical problems are.

Think the market is going to solve this when the signal back to the risk takers is strong enough.

Encouraged to see across the different groups that the solution from a system perspective was identified. To focus on one component, either a precursor or a piece of hardware, to drive to a low price in that area <u>is</u> a system approach.

Need to have more clarity on precursors that have already been developed. If you want lignin it comes from an industry that is already there. If you get it from a bioenergy business, there is integration where you are going to get raw material you need to consider that approach as well - quickly.

Issue is integration among competitive pressures

A systems approach is key; risks and rewards need to be balanced across supply chain

Want clarity on what's next – again, how will the world be different. Need a roadmapping activity to list the objectives and how we're going to collectively achieve them.

Implement, implement, implement. It would have helped early in sessions if we had a full description of the technology that has been developed.

Standardization of end-usage would help with applications.

Need to recognize there will be a lot of effort required.

Appreciated taking a technology to applications across the sectors.

At the end of the day no one is going to change their business model.

The government can play an important role to help get different people together. Government should do those things that we can't do for ourselves.

Standardization and viability of design materials would make our job a lot easier for implementation. Standardizing across the suppliers.

Need to focus on $ saved per auto or $ saved per MW of electricity generated because what we are doing is reducing weight. It may be more $/lb but more useful.

Key is public-private partnerships. Looking forward to the report as well as what is next.

From a university – encouraged to hear there is interest in generating people with skills

Good seeing things from beginning of fiber made to when it becomes a product. Good seeing fiber in other applications.

What is the real cost per pound in auto industry – how much weight does the car lose, what is the secondary benefit? What is the real cost per pound when you get to the end use?

It was interesting to find out that the capital investment issue was universal across other industries

From a supplier – R&D for auto is cutting into cash flow. Labs would be very helpful.

Similarity of results means people want to work together.

Maybe future session where different companies -- different points in supply chain -- can exchange requirements. That would be helpful.

It would have been helpful to see more of a global status of technology where it is not just a narrow view here. Also, broader applications beyond the high-end type. Anxious to see and optimistic of what might come next.

This workshop showed complexity of the matter. Consider what practical implementation can be done in short- to medium-term. We have to make that bridge. Very important in the manufacturing industry. We need firm results in next 2-3-4 years.

Timing is critical for carbon fiber to be integrated into renewable technology applications. We need finished product and goods we can use today -- we can use at a price level that meets expectation of the industry at large, e.g., reduced cost for wind generation technology.

In any economic situation, if there is one group that puts enough time, resources, and dollars on the table then they will ultimately be winners in the end. There is lots of expertise here. We go back home and somebody will decide to make the move whether or not the government is there to throw money at it and reduce the risk.

We did the easy part. Carbon fiber is going to move in the industry eventually. The hard part is if the government wants cost effective wind generation, more petroleum savings in vehicles, and they want it to happen sooner it's going to take big bucks to implement here and make it happen sooner rather than eventually.

A roadmap would be a very useful tool. As we move forward let's not forget that not 100% of the value happens as soon as you get to $5/lb fiber. There is a lot more to be had in the chain. As we go forward it would be helpful to have benchmarks against which to measure progress.

Report needs to clearly state who is going to do what and when. In a couple of years we should have a follow up meeting to see what we did over the last 2 years.

From a resin manufacturer: Broad spectrum of people here. The supply chain is extremely fragmented, and there is competition from traditional materials. As we approach different industries we need one unified voice.

We should do a meeting like this every year.

Cost/lb of final product – airplanes cost between 100-1000 $/lb. The goal is under $100/lb.

Diversity is excellent. How quickly are we going to get this done? We've been talking about cost of fiber for many years, at least since 2002. We need to get to the 3 to 5 things everyone had on their list, and move collectively.

This workshop comes at right time. Hopefully with support of DOE ITP, Wind, Biomass, VTP and availability of stimulus money, DOE can jump on implementation and take on one or a combination of recommendations.

The exchange of ideas shows us what we know and what we don't know. It pointed to expectations both realistic and unrealistic. Many of the things we are looking for are already out there in various government programs. They need to be adapted as well as adopted. You want it fast, cheap, and right – you can have two.

This feedback is the most interesting thing. Conduct a follow-up survey to get additional feedback from participants and keep the momentum going

Important to recognize that wind and auto have very similar constraints in terms of cost and quality.

We have 50 years of carbon fiber manufacturing and we are still talking about low cost carbon alternatives. We need something that is going to cause a fundamental change so that the economics work; we need a disruptive technology-precursor or manufacturing of materials, etc.

It would be nice to know what a pound of weight saved in the auto industry is worth.

It was good that the breakout groups came to the same conclusions.

# 6. Needs, Actions, Next Steps

Comments and recommendations by the workshop participants pointed at several different needs, actions, and next steps. Common themes are shown below:

- Developing “carbon fiber” should not be done in a vacuum. A systems approach is needed, balancing risks and benefits across the entire process. Although carbon fiber development itself is a key component, one cannot forget the manufacture of composites. Understanding the value stream of carbon fiber would be beneficial.
- There is a need for a breakthrough in precursors and in manufacturing processes. Precursors in particular needs some focus. One place to start would be having more clarity and accessibility to documentation on what precursors have already been developed.
- While the automotive and wind industries are primary targets for low-cost carbon fiber composites in the energy field, investigating other applications such as electrical transmission and distribution lines, oil rigs, and airplanes should be pursued.
- Currently, carbon fiber end-users are composed of a diverse group of stakeholders that are fragmented. These stakeholders should collaborate and discuss their requirements so that there is an approach for widespread use of carbon fiber. Incentives are needed for this. The DOE can play a key role to help facilitate this collaboration.
- The DOE programs with stake in carbon fiber composite products should develop a roadmap that includes a clear list of metrics and objectives and an action plan as to how they can be achieved. Targets and benchmarks are necessary in order to define where we need to go and how we are progressing. It is important that the roadmap indicate specifically what the short- and mid-term objectives are. Some of the benefit is achieved through something that is developed along the way, not just the end-target.
- Cost per pound of carbon fiber in itself is not necessarily a proper target. One suggestion is cost per pound of end-use application, perhaps in terms, for instance, of dollars saved per vehicle, or per kWh of electricity.
- Understanding carbon fiber composite status and needs on a global scale is important.
- It would be useful to conduct a survey based on the results from the workshop to get additional feedback and perspectives and convene a follow-up workshop in one to two years that would “keep the momentum going” in this research area.

# Appendix A. Agenda


**Low Cost Carbon Fiber Composites in Energy Applications**
**March 3-4, 2009**
**Joint Institute for Computational Sciences, Building 5100**
**Oak Ridge National Laboratory**
**Oak Ridge, Tennessee**

**March 3, 2009**

| | | |
|---|---|---|
| 7:15 a.m. | Buses Pick Up at Comfort Inn | |
| 8:00 a.m. | Registration<br>*Coffee and Continental Breakfast in Registration Area* | |
| 8:30 a.m. | Opening Plenary Session | Raymond G. Boeman<br>*Workshop Chairman*<br>*and Director, Transportation Program*<br>*Oak Ridge National Laboratory* |
| 8:30-8:35 a.m. | Welcoming Remarks | Dana Christensen<br>*Associate Laboratory Director*<br>*Energy and Engineering Sciences Directorate*<br>*Oak Ridge National Laboratory* |
| 8:35-8:40 a.m. | Meeting Goals and Objectives | Raymond G. Boeman |
| 8:40-8:45 a.m. | Importance of Carbon Fiber and Composite Technologies | Patrick B. Davis<br>*Manager, Vehicle Technologies Program*<br>*Office of Energy Efficiency and Renewable Energy*<br>*U.S. Department of Energy* |
| 8:45-9:10 a.m. | History and Status of Carbon Fiber Composites | Mohamed Abdallah<br>*President*<br>*MGA Advanced Composites and Engineering Co.* |
| 9:10-9:30 a.m. | Carbon Fiber Composites Technology Development | C. David Warren<br>*Manager, Transportation Materials Program*<br>*Oak Ridge National Laboratory* |
| 9:30 a.m. | Break | |

| | | |
|---|---|---|
| 9:45 a.m. | Overview of Technologies and Markets | |
| 9:45-10:10 a.m. | Carbon Fiber in the Automotive Industry . . . The Holy Grail or Reality? | Jim deVries<br>*Staff Technical Expert*<br>*Research and Innovation Center*<br>*Ford Motor Company* |
| 10:10-10:35 a.m. | Wind Applications | Jose Zayas<br>*Manager, Wind Energy*<br>*Sandia National Laboratory* |
| 10:35-11:00 a.m. | General Industrial Applications | Scott Finn<br>*Chief Engineer of Composites*<br>*GE Research* |
| 11:00 a.m. | Breakout Session Instructions | Ed Skolnik<br>*Lead Workshop Facilitator and*<br>*Program Manager, Energetics, Inc.* |
| 11:10 a.m. | Break and Move to Breakout Session Rooms<br>*Lunch in Breakout Rooms* | |
| 11:30 a.m. | Breakout Sessions Topic 1<br>*Technical Track: RD&D Needs*<br>*Business Track: Market Issues and Challenges* | |
| 2:45 p.m. | Breakout Sessions Topic 2<br>*Technical Track: Identification of Key RD&D Activities to Address Needs*<br>*Business Track: Identification of Key Deployment and Scale-Up Activities to Address Market Issues and Challenges* | |
| 5:00 p.m. | Buses Depart Campus for Flatwater Event Center | |
| 5:45 p.m. | Hosted Dinner with Presentation on *Composite Structures: The First Hundred Years* | Billy Roeseler<br>*Associate Technical Fellow*<br>*The Boeing Company* |
| 7:15 p.m. | Buses Depart Flatwater Event Center for Comfort Inn | |

**March 4, 2009**

| | | |
|---|---|---|
| 7:45 a.m. | Buses Pick Up at Comfort Inn | |
| 8:30 a.m. | Breakout Sessions Topic 3<br>*Coffee and Continental Breakfast in Breakout Rooms*<br>*Technical Track: Implementation Approaches*<br>*Business Track: Implementation Approaches* | |
| 10:15 a.m. | Break and Move to Auditorium, Joint Institute for Computational Sciences, Building 5100 | |
| 10:30 a.m. | Reports from Breakout Sessions | Ed Skolnik<br>and Breakout Group Representatives |

| | | |
|---|---|---|
| 11:15 a.m. | Advancing Technology Deployment through Industry-Government Partnerships | Alan Liby<br>*Manager, Industrial and Economic Development Partnerships* |
| 11:45 a.m. | Working Lunch: Closing Roundtable Discussion and Wrap-up | Ed Skolnik |
| 1:00 p.m. | Bus Departs for Comfort Inn and Knoxville Airport | |
| 1:00 p.m. | Tours of Carbon Fiber R&D Facilities | |
| 3:00 p.m. | Tours End and Last Bus Departs for Comfort Inn and Knoxville Airport | |

# Appendix B.  Final Participant List

**Low Cost Carbon Fiber Composites**
**for Energy Applications**
March 3-4, 2009
Oak Ridge, Tennessee

**Mohamed Abdallah**
Consultant
MGA-Advanced Composites & Engineering
801-466-9310
agm1144@yahoo.com

**Rashid Abdul**
CBO
Gamesa Technology
215-710-3189
rabdul@gamesacorp.com

**Thomas Ashwill**
Project Manager
Sandia National Laboratories
505-845-8457
tdashwi@sandia.gov

**Eliot Assimakopoulos**
Business Development Manager
General Electric
518-387-7639
assimako@ge.com

**Peter Axegard**
Research Director
STFI-Packforsk
468-6767-221
peter.axegard@stfi.se

**Darren Baker**
Oak Ridge National Laboratory
865-241-6243
bakerda@ornl.gov

**Frederick Baker**
Distinguished R&D Staff
Oak Ridge National Laboratory
865-241-1127
bakerfs@ornl.gov

**Steven Baldini**
Director, New Product Applications
Zoltek
314-291-5110 Ext. 211
ric.baldini@zoltek.com

**Glenn Barefoot**
Corporate Marketing Manager
STRONGWELL
276-645-8000
gbarefoot@strongwell.com

**Rick Battiste**
Oak Ridge National Laboratory
865-574-0736
battisterl@ornl.gov

**Lionel Batty**
Director of Corporate Research and Development
GraffTech International
216-676-2300
lionel.batty@graftech.com

**Paul Bencin**
International Sales Mgr.
C.A. Litzler
216-267-8020 Ext. 603
pbencin@calitzler.com

**Alain Bergeron**
Energy and Secondary Water Treatment Supervisor
Kruger Wayagamack Ing
819-373-9230 Ext. 367
abergeron@wa.kruger.com

**Paul Bissett**
Project Lead
Weyerhaeuser
253-924-6528
paul.bissett@weyerhaeuser.com

**Robert Blackmon**
Vice President - Process Systems Division
Harper International
815-703-1666
rblackmon@harperintl.com

**Craig Blue**
Director, Industrial Technologies Program
Oak Ridge National Laboratory
865-574-4351
blueca@ornl.gov

**Raymond Boeman**
Director Transportation Technologies Program
Oak Ridge National Laboratory
865-946-1203
boemanrg@ornl.gov

**Douglas Bradley**
Composite Material Specialist
General Dynamics
586-825-8993
bradledj@gdls.com

**Joseph Carpenter**
Technology Area Development Manager
U.S. Department of Energy
202-586-1022
joseph.carpenter@ee.doe.gov

**William Clinkscales**
Director of Sales and Marketing
Structural Composites Industries
909-444-2500
wclinkscales@scicomposites.com

**Jose Miguel Contreiras**
Board Member
FISIPE
+351 (212) 066138
jmcontreiras@fisipe.pt

**Francis Cretella**
Research Associate
PPG
704-434-2261 Ext. 132
cretella@ppg.com

**Eric deNijs**
Product Engineer
Cosma Engineering
248-619-8137
edenijs@cosma.com

**Alex DeTrana**
Commercialization Manager
Oak Ridge National Laboratory
865-576-9682
detranaag@ornl.gov

**Jim deVries**
Staff Technical Expert
Ford Motor Company
313-322-3494
jdevries@ford.com

**Cliff Eberle**
Composites Technology Development Manager
Oak Ridge National Laboratory
865-574-0302
eberlecc@ornl.gov

**Scott Finn**
Chief Engineer
General Electric
518-387-4064
finn@ge.com

**Nidia Gallego**
Oak Ridge National Laboratory
865-241-9459
gallegonc@ornl.gov

**Monterey Gardiner**
Tech. Dev. Manager
U.S. Department of Energy
202-583-1758
monterey.gardiner@ee.doe.gov

**Stephen Goguen**
General Engineer
U.S. Department of Energy,
Office of the Industrial Technologies Program
202-586-8044
stephen.goguen@ee.doe.gov

**John Gorog**
Consultant
Retired Weyerhaeuser
253-670-2867
pmgorog@comcast.net

**Kathy Graham**
Oak Ridge National Laboratory
865-946-1861
grahamkj@ornl.gov

**Rondle Harp**
General Engineer - Project Manager
U.S. Department of Energy,
National Energy Technology Laboratory
304-285-5436
rondle.harp@netl.doe.gov

**David Hartman**
Senior Fellow
Owens Corning
740-321-5399
dave.hartman@owenscorning.com

**Takao Hayashi**
Manager
Nissan Technical Center North America, Inc.
248-488-4604
hayast2@ntcna.nissan-usa.com

**Joseph Hayes**
President
American Kynol, Inc.
914-769-0101
jhayes@kynol.com

**Roger Hill**
Project Manager
Sandia National Laboratories
202-586-0960
roger. hill@hq.doe.gov

**David Icke**
Advanced Electron Beams
978-658-8600 Ext. 170

**Ryutaro Izumi**
VP Sales and Marketing
Izumi International, Inc.
864-288-8001
rizumi@izumiinternational.com

**D. Ray Johnson**
Manager, Transportation Materials
Oak Ridge National Laboratory
865-576-6832
johnsondr@ornl.gov

**Mauricio Justiniano**
Engineer-Financial Analyst
Energetics Incorporated
410-953-6205
mjustiniano@energetics.com

**Michael Keeler**
V.P. Advance Technology
Hendrickson
630-910-2825
mkeeler@hendrickson-intl.com

**Hamid Kia**
Lab Group Manager
General Motors
586-986-1215
hamid.g.kia@gm.com

**John Koenig**
Head, Materials Research Department
Southern Research Institute
205-581-2436
koenig@sri.org

**James Kolb**
Sr. Director, Automotive
American Chemistry Council
248-244-8920
James_kolb@americanchemistry.com

**Gary Krause**
Michigan Economic Development
Corporation (MEDC)
517-241-0117
krauseg@michigan.org

**Christopher Layton**
Sales Representative
Fi-Tech, Inc.
804-794-9615
clayton@fi-tech.com

**Ben Lemmons**
Sales Manager
American Starlinger Sahm
864-297-1900
blemmons@starlingersahm.com

**Eric Leonard**
Manager
Toyota Motor Engineering &
Manufacturing North America, Inc.
734-995-7170
eric.leonard@tema.toyota.com

**James Leslie**
CEO
Advanced Composite Products
and Technology Inc. (ACPT)
714-895-5544
j1leslie@acpt.com

**Alan Liby**
Oak Ridge National Laboratory
865-576-4212
libyal@ornl.gov

**Ronny Lomax**
Oak Ridge National Laboratory
865-574-3551
lomaxrd@ornl.gov

**Rick Lowden**
Analyst
ODUSD (IP)
703-601-5003
rick.lowden@osd.mil

**Gary Lownsdale**
Engineering Manager
Plasan Carbon Composites
802-445-1700 Ext. 2024
glownsdale@aol.com

**Brian Marchionini**
Program Manager
Energetics Incorporated
202-406-4109
bmarchionini@energetics.com

**Michael Muser**
Composite Business Manager
Ingersoll Machine Tools
815-987-6138
mmuser@ingersoll.com

**Amit Naskar**
Oak Ridge National Laboratory
865-576-0309
naskarak@ornl.gov

**Stephen Nolet**
Principal Engineer
TPI Composites, Inc
401-247-4009
snolet@tpicomposites.com

**Robert Norris**
Group Leader
Oak Ridge National Laboratory
865-576-1179
norrisrejr@ornl.gov

**Steven H Olson**
Lean Leader, Renewables Quality
General Electric, Wind
864-254-2816
steven.olson@ge.com

**Peter Oswald**
V.P. Marketing
Toho Tenax America, Inc.
865-354-5518
poswald@tohotenax-us.com

**Soydan Ozcan**
Oak Ridge National Laboratory
865-241-2158
ozcans@ornl.gov

**Felix Paulauskas**
Distinguished Scientist
Oak Ridge National Laboratory
865-576-3785
paulauskasfl@ornl.gov

**Jeanne Phillips**
Administrative Assistant
Oak Ridge National Laboratory
865-576-0382
phillipsjr@ornl.gov

**Mark Rivers**
Project Manager
Despatch Industries
952-469-8130
mark.rivers@despatch.com

**Jeffrey Robbins**
Director R&D
Meridian Automotive
734-604-0614
jrobbins@meridianautosystems.com

**Billy Roeseler**
Assoc Tech Fellow
Boeing
425-442-8499
wm.g.roeseler@boeing.com

**Vikram Singh**
Sr Director Engineering
Varian Semiconductor Equipment Associates
978-282-8302
vikram.singh@vsea.com

**Philip Sklad**
Program Manager
Oak Ridge National Laboratory
865-719-4853
skladps@ornl.gov

**Edward Skolnik**
Prog Mgr/Sr. Scientist
Energetics Incorporated
202-406-4125
eskolnik@energetics.com

**E Phillip Smith**
Sr. Innovation Associate
Eastman Chemical Company
423-229-6883
epsmith@eastman.com

**Kennith Smith**
R&T Mgr., Global Fibers
Hexcel
256-340-4172
Ken.Smith@hexcel.com

**Brennan Smith**
Program Manager, Wind
and Water Power Technologies
Oak Ridge National Laboratory
865-241-5160
smithbt@ornl.gov

**Brad Spear**
Director of Business Development
Energetics Incorporated
202-406-4131
bspear@energetics.com

**Dave Stinton**
Manager, DER Materials Program
Oak Ridge National Laboratory
865-574-4556
stintondp@ornl.gov

**Karla Strong**
Materials Engineer
U.S. Air Force
937-255-6977
karla.strong@afrl.af.mil

**Rogelio Sullivan**
Program Manager
North Carolina State University
919-513-3330
rasulliv@unity.ncsu.edu

**Hubertus Thomeer**
Engineering Manager
Schlumberger
281-285-5630
thomeer1@slb.com

**Balazs Tolnai**
Manager Product Development
Kruger Inc.
514-343-3100 Ext. 2193
balazs.tolnai@kruger.com

**Kathi Vaughan**
Business Analyst
Oak Ridge National Laboratory
865-946-1206
vaughankh@ornl.gov

**Nikhil Verghese**
Research Leader
Dow Chemical Company
979-238-2706
neverghese@dow.com

**Dave Warren**
Program Manager
Oak Ridge National Laboratory
865-574-9693
warrencd@ornl.gov

**Daniel Webb**
Oak Ridge National Laboratory
865-574-4959
webbcd@ornl.gov

**Matthew Weisenberger**
Engineer Associate
University of Kentucky
859-257-0322
matt@caer.uky.edu

**Ken Yarborough**
Oak Ridge National Laboratory
865-574-6622
yarboroughkd@ornl.gov

**Jose Zayas**
Manager - Wind Energy
Sandia National Laboratories
505-284-9446
jrzayas@sandia.gov

**Edward Zenk**
Sr. Development Engineer
Navistar, Inc.
260-461-7617
edward.zenk@navistar.com

**Dick Ziegler**
Senior Vice President
Sentech
865-805-8293
RZiegler@sentech.org

# Appendix C.  Contact Information

## *ORNL Workshop Coordination Team:*


Craig Blue
blueca@ornl.gov

Raymond G. Boeman
boemanrg@ornl.gov

Cliff Eberle
eberlecc@ornl.gov

Jeanne Phillips
phillipsjr@ornl.gov

Phil Sklad
skladps@ornl.gov
philip.sklad@ee.doe.gov

Kathi Vaughan
vaughankh@ornl.gov


## *Workshop Facilitation Team:*


Mauricio Justiniano
mjustiniano@energetics.com

Brian Marchionini
bmarchionini@energetics.com

Edward Skolnik
eskolnik@energetics.com

Brad Spear
bspear@energetics.com