B. Development of Next-Generation Programmable Preforming Process

Co-Principal Investigator; Robert E. Norris, Jr
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-6053
(865) 576-1179; fax (865)-574-8257; e-mail: norrisrejr@ornl.gov

Co-Principal Investigator: Raymond G. Boeman
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-6053
(202) 586-0785; fax (202) 586-7409; e-mail: boemanrg@ornl.gov

Field Project Manager, Composites: C. David Warren
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-6065
(865) 574-9693; fax: (865) 576-4963; e-mail: warrencd@ornl.gov

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

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Objectives

- Develop the next-generation of low-cost fiber-preforming technologies based on programmable, robotic-controlled, directed chopped-fiber processes for the application of
  - low-cost carbon fiber
  - reinforced thermoplastics
  - hybrid glass-carbon
- Develop supporting technologies required to successfully implement the process technology including
  - preform characterization (e.g., permeability, areal density uniformity)
  - preform process modeling for process effects analysis
- Conduct parametric process studies to investigate fundamental process effects and establish process-property relationships.
- Conduct requisite molding investigations—experimental and through modeling—to elucidate relationship between preform characteristics and moldability.

Approach

- Establish a base research programmable, robotic preforming system for which advanced capabilities (e.g., new chopper designs) can be developed and evaluated.
- Establish a highly instrumented and controlled research molding capability to isolate and investigate the effects of process variables on moldability and mechanical properties.

- Develop new severing technology to facilitate the implementation of low-cost carbon, reinforced thermoplastics, and hybrid glass-carbon products.

Accomplishments

- Completed preliminary acceptance testing on the P4 machine at Aplicator with several recommended improvements to both hardware and software to be implemented prior to shipment.
- Upgraded laboratory utilities to provide dedicated 600A and plant air services to the P4 machine.
- Coordinated with shippers, customs, and plant facilities and equipment crews to get P4 system containers delivered to ORNL and placed in convenient staging locations, and assisted Aplicator crew on initial 3-week effort to complete system basic mechanical installation.
- ORNL personnel completed robotic-specific training at the ABB US Training facility.
- Hosted Aplicator personnel on return 3-week visit to complete installation, checkout, and training of ORNL personnel in operations, maintenance, and system programming. This completed activities necessary for contractual acceptance of the P4 system.
- Obtained various combinations of fibers and binders to establish materials baselines for comparison with previous and ongoing P4 work being conducted by the ACC. Also obtained materials to be used in establishing baseline for related permeability test development.
- Built a sensor test rig and evaluated numerous concepts and techniques for fluid detection sensors and associated data acquisition system in the in-plane permeability test machine. Chose best sensor candidate and set up lab-scale production to complete ~250 sensors for system operation.
- Completed radial flow permeability measurement system and associated controls and data acquisition systems specifically configured for the ORNL-developed sensor system. System checkout and initial permeability measurements to compare with literature values were being taken at the end of this reporting period.
- Initiated planning and identification of equipment requirements necessary to evaluate feasibility of laser severing technology.
- Developed requirements for research press, experimental mold, and injection-molding machine with assistance from the Automotive Composites Consortium Processing Group members. Requirements were utilized to prepare and issue RFQ's for this equipment. Evaluation of submitted bids to get this equipment under contract was being completed at the end of this reporting period.
- Previously developed general modeling approach was expanded to include a new algorithm that made possible quick simulation of tens of thousands of fibers, new algorithms for fast void discovery, an initial model for shaped substrate, and an initial model for mat compression
- Completed ORNL/DOE "Critical Outcome" milestone by demonstrating system functionality of the performing machine in a variety of trials including generation of various spray patterns, preform thicknesses and cut fiber lengths during testing.

Future Direction

- Complete procurement, installation, and integration of injection/compression press, general purpose mold with associated heating system, and resin injection machine.
- Upgrade laboratory structure and utilities as required to accommodate the equipment as described above.
- Demonstrate functionality and utility of the in-plane permeability measurement system by verifying data quality in comparison with data in the literature and conducting measurements on preforms made by simulated split-tow products of varying tow-size.
- Evaluate preform process models relative to physical preform characteristics and expand model capability as resources permit.

- Conduct initial preforming studies with low-cost carbon fiber and various forms incorporating reinforcement and thermoplastic matrix materials "co-processed" through the performing machine.
- Construct and test through-thickness permeability rig as funding and other resources permit.
- Initiate bench-top studies of advanced severing technology.

Introduction

Polymer-matrix composite materials offer a number of benefits in "lightweighting" of automotive and heavy vehicles, including greater stiffness and strength per unit weight than conventional materials, easier formability, less corrosion susceptibility, the ability to tailor properties to specific load requirements, and enhanced noise and vibration damping. However, widespread implementation of carbon-fiber composites, which offer among the greatest mass savings potential, requires lower cost materials and processes than are currently available. Advanced preforming processes offer opportunities to facilitate the widespread use of carbon composites.

Robotic-controlled, programmable, directed-fiber preforming processes have demonstrated exceptional value for rapidly preforming large, glass-reinforced, automotive composite structures. Due to their unique features and flexibility, and to their inherently low scrap rate, they are the most viable candidate processes for making affordable carbon-fiber preforms for a variety of structural automotive components. The Automotive Composites Consortium (ACC) has implemented the Programmable Powdered Preform Process (P4), with glass fibers, very successfully in its truck box program—Focal Project 2 (FP2). Original equipment manufacturers (OEMs) have transferred the technology to commercial applications such as the General Motors (GM) Silverado pickup box and the Aston Martin Vanquish body-side.

Analyses have indicated a potential for greater than 60% mass savings for a carbon-fiber-intensive body-in-white under the assumption of a thickness design constraint of 1.5 mm. The analyses also indicate the potential of saving an additional 15% if the thickness constraint is reduced to 1 mm. Unfortunately, evidence suggests that 1.5 mm may be a practical limit for liquid molding. However, thermoplastics preforms, in which the matrix and fiber are both deposited in the preforming step, offer a potential path to obtaining thinner sections, and consequently additional mass savings as well as greater potential for recyclability. Hybrid-fiber performs offer another potential benefit in terms of economics and property enhancement.

Approach

The objective of this project is to advance directed-fiber preforming processes to effect a further reduction in vehicle mass—relative to glass-fiber composites—while maintaining the economical advantages of net-shape preforming. The project will be executed in three focus areas corresponding to three materials systems: carbon fiber, reinforced thermoplastics, and hybrid glass-carbon fiber. Each focus area will consists of four main tasks concentrating on (1) materials developments, including new fiber product forms and binders; (2) machine developments, particularly new severing technology; (3) process developments, for example, to control areal density uniformity and preform anisotropy; and (4) development of supporting technologies such as modeling and preform characterization techniques. Furthermore, this project will undertake to develop sufficient understanding of fundamental aspects of the process and their effect on preform quality and mechanical properties in the molded part. As such, this project will support, augment, and facilitate the current and future research activities undertaken in the "Development of Manufacturing Methods for Fiber Preforms" project (see report 4.A).

Procurement and Installation of Preforming System

Central to this effort is the implementation of a research-oriented, robotic-controlled, programmable preforming system for installation in the polymer composites laboratories of the Metals and Ceramics Division at the Oak Ridge National Laboratory. This system establishes the base for future hardware developments as well as serving as a research instrument on which parametric process studies will be conducted. A competitive solicitation was issued in April 2004, vendor selection made in May 2004, and a purchase order let in June 2004. Applicator System AB of Mölnlycke, Sweden, was selected to design and build the system.

The ORNL system was ready for initial acceptance testing and approval for shipment late in the first quarter of FY 2005. This review took place in at Aplicator's manufacturing facility in Sweden in December of 2004. ORNL had a technical and a contractual representative present at this review who were assisted by a technical representative from the Processing Group of the Automotive Composites Consortium. Although the technical review identified several software and hardware items requiring further adjustment and minor modification, the system was deemed ready for shipment upon completion of those items.

The system (see Figures 1 and 2) has a footprint of 9 by 15 m, contains a robot with 7° of freedom and can produce preforms up to approximate dimensions 1 m × 1.2 m × 1.8 m. On the head of the robot is mounted a chopper unit that incorporates the main chopper for spraying the reinforcement fibers and a surface veil chopper. Fiber length is adjustable on-the-fly in two ranges, 20–85 mm and 90–200 mm, as well as continuous. Fiber output is variable and can be as high as 3500 g/min.

Facility modifications and upgrades were required in order to install this machine in the Composites Processing Laboratory at ORNL.

Testing at Aplicator revealed that the machine actually required a single power line supply of at least 500A, versus projections as the machine was being constructed that the unit could be operated from reallocation and combining the capacities from two existing 400A supply lines already present in this laboratory. To provide the necessary capacity, a completely new 600A supply line had to be established in this laboratory and a new building transformer activated. Also beyond the original planning was the need for extensive logistical and rigging support in handling of the large sea-land containers in which the unit was shipped from Sweden. As planned, other support was provided for provision of plant air and overall coordination of activities.

In addition to installation of the P4 system itself and provision of utilities, the use of chopped fibers and powdered binders necessitates that the large air stream utilized to assist in direction, placement, and setting of the prefrom must be filtered prior to release of the air back into the environment. ORNL staff worked with Aplicator, ACC staff, and representatives of firms providing filtration units and installation services to choose an appropriate filtration unit and design this system to fit within facility constraints. Procurement, installation of the filtration unit (shown in Figure 3), and interface with the P4 machine was contracted to a construction firm approved by the building owner as a turn-key job. Also a part of the job was provision of a makeup air system since the filtered air is being exhausted exterior to the building and the building itself is already operating at a higher than desired negative air pressure environment.

During the initial multi-week visit by personnel from Aplicator to install the P4 machine at ORNL, initial system checkout and rudimentary training were conducted. The system met operational targets and items identified for improvement during the pre-shipment evaluation had been completed as desired. Having a basic understanding of the nuances of the ORNL machine and its ABB robotic system, operational personnel from ORNL were sent to robot-specific training conducted at the ABB US Training facility. With this training and some additional checkout activities completed at ORNL, Aplicator returned for more in-depth training and system checkout. During the interim, some minor hardware and software difficulties had been identified. This training has now been completed and the technical difficulties rectified.

As a second, but no less important focus of this follow-on visit, Aplicator worked with ORNL to develop general purpose programs for making the flat plaques that will serve as baseline for much of the initial ORNL work in establishing the machine operational envelope. These programs provide an easily modifiable platform for beginning the development work projected for working with new

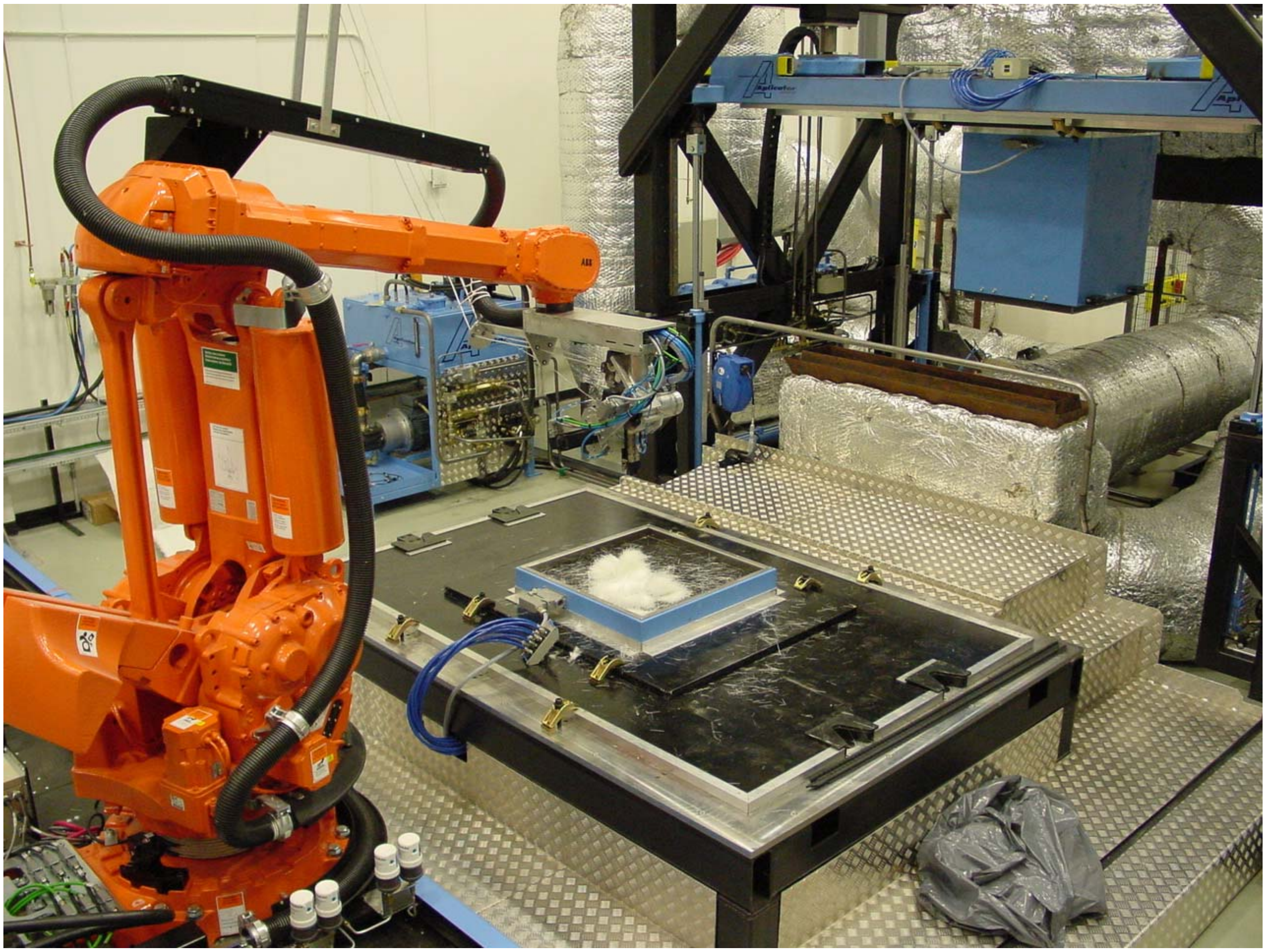

Figure 1. ORNL's new robot-controlled and actuated, programmable preforming system.

Figure 2. Fiber delivery system and operating controls for ORNL's preforming system.

Figure 3. External filter system for ORNL's preforming system.

materials and processes in advancing the state-of-the-art for performing technology using this type of equipment. In fact, these programs were indeed utilized with minor modification in order to meet an ORNL/DOE "Critical Outcome" milestone by demonstrating system functionality in a variety of trials including generation of various spray patterns, preform thicknesses and cut fiber lengths during testing. Future work will also include modifications to the base system in facilitating advanced fiber product forms, including low-cost carbon fiber, reinforced thermoplastics, and glass-carbon hybrids.

Procurement of a Press, Mold, and Injection Machine

Key to being able to demonstrate the advances achieved in performing technology is the ability to demonstrate that these advances translate into improvements in actual completed composites. The best way to effect this demonstration is through injection of resin into the preform and compression of the preform and resin into a composite in the manner in which this would be accomplished in actual composite manufacturing.

During this period, efforts were initiated to identify the most appropriate equipment necessary to do this on a research basis. ORNL staff worked with members of the Automotive Composites Consortium's Processing Group to quantify process equipment requirements and initiate activities necessary to procure a research press, general purpose mold, and injection machine. These requirements were turned into formal RFQ's for designing and building these systems, which were issued to companies that had been identified through ORNL and ACC interactions as having potential to meet or exceed all performance targets. The intelligent-leveling press (see Figure 4) is being designed to accommodate various molds and molding processes and will be instrumented above routine standards in order to provide more process details in experimental research. Nominal pressing capacity is 750 tons. The general purpose plaque mold (see Figure 5) will be designed for instrumented experiments using Structural Reaction Injection Molding (SRIM), Compression Molding of Reinforced Thermoplastics, and Sheet Molding Compound (SMC) processes. This equipment will

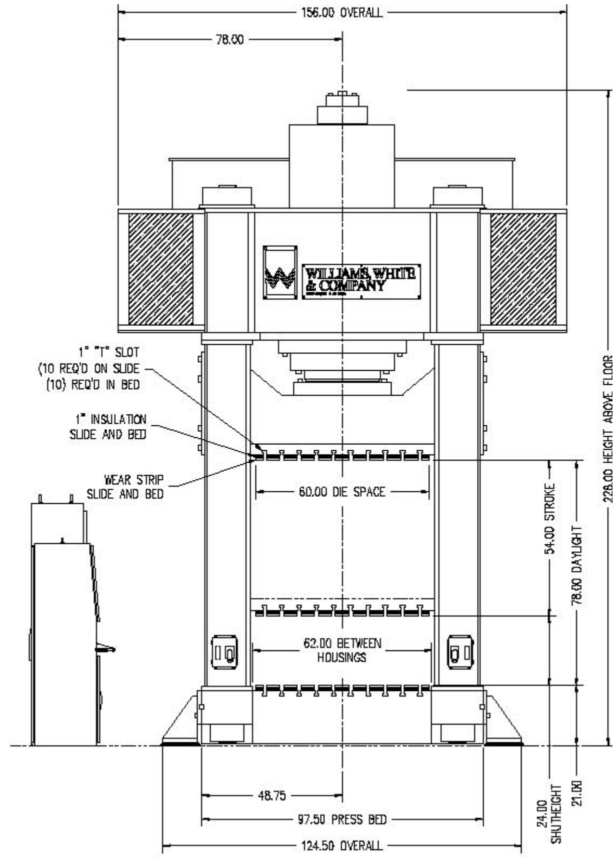

Figure 4. Intelligent-Leveling, 750-net-ton, Injection/Compression Press being procured by ORNL.

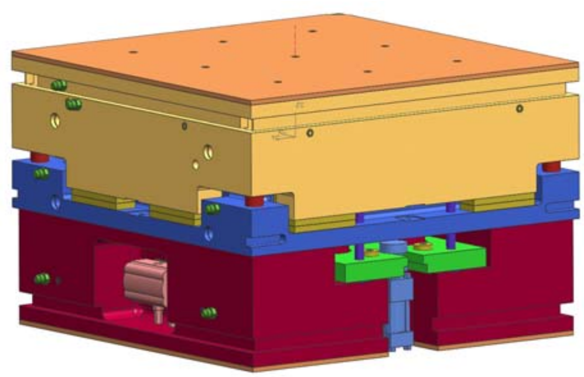

Figure 5. General Purpose Flat Plaque Mold for SRIM, SMC, and Thermoplastics.

allow ORNL to demonstrate preform advances while further investigating advances in the various molding processes themselves.

At the conclusion of this reporting period, the bid packages have been received and the orders will be placed in early FY 2006. It is anticipated that the mold will be completed in the early portion of the second quarter of FY 2006 while the press will be completed late in the third quarter or early in the fourth quarter of FY 2006. Both will be shipped to ORNL and installed as soon as possible after initial acceptance testing at the vendors. A completion date for the injection machine is dependent on vendor selection, which has not been completed at this time. Also to be determined is need for any structural upgrades needed for the facility to support this equipment. An engineering study is planned for early FY 2006 to quantify these needs and provide any necessary design details along with a cost estimate.

Permeability Measurement

It has been found that injection-compression offers distinct advantages over injection-only liquid molding for the infiltration of high-volume fraction preforms. Consequently, both the in-plane permeability and the through-thickness permeability affect the moldability of the part. Accordingly, two novel research instruments are under development that will provide experimental data to characterize the three-dimensional permeability of the fiber mat preform.

Work continues on the development and implementation of an in-plane rig (see Figure 6) with a flow capacity of 0.33 gpm and a fluid capacity of 2 gal. It can be operated in either constant-flow or constant-pressure mode under feedback control. Maximum pressure and fluid viscosity are 100 psi and 5 poises, respectively. Both platens are instrumented with sensors—a total of 218 sensors—to monitor the flow-front with resolution of 0.25 in. The initial development focused on a sensor concept developed through subcontract to Prof. Richard Parnas at the University of Connecticut. It consisted of a recessed insulated conductor that generates a voltage when the conductive fluid bridges the sensor and the metallic plate. Although the conductive sensor appeared to work adequately in the University of Connecticut laboratory, it has been problematic when implemented in the system at ORNL. Although some effort was continued to improve the accuracy and reliability of the conductive sensors, it was decided to reopen the sensor selection to a variety of concepts identified by the staff at ORNL.

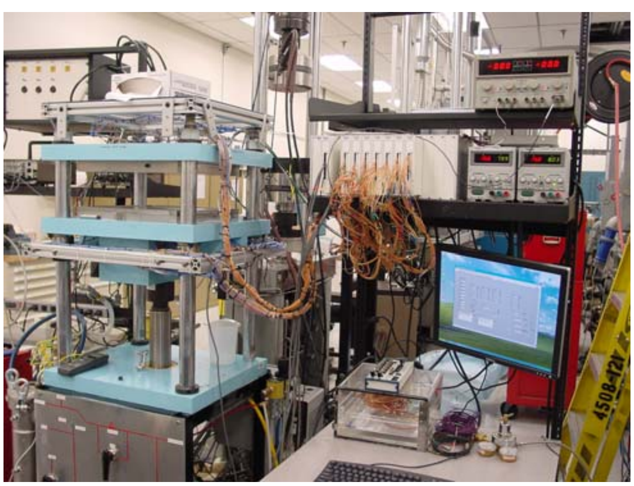

Figure 6. Radial Permeability Test Rig showing associated data acquisition and monitoring station.

A smaller-scale "sensor test rig" (Figure 7) was fabricated in order to facilitate evaluation of several sensor concepts in a simpler environment than the full-scale test rig. Based on tests of a number of sensor concepts in this rig, it was decided to focus further development and implementation on a novel concept for a temperature sensor that would demonstrate fluid contact by a significant change in temperature caused by the cooling of the test fluid passing over its surface. This potentially patentable concept was successfully evaluated in the sensor test rig and a full complement of sensors for the in-plane test rig were manufactured and installed in the full-scale test rig.

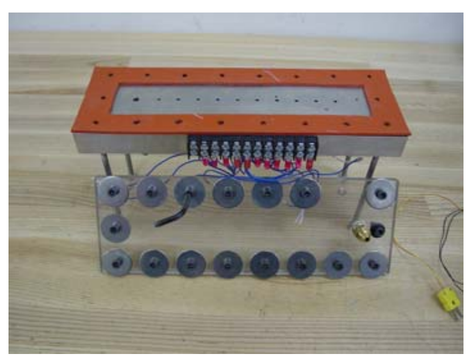

Figure 7. Test rig developed to evaluate sensors that will identify moving fluid front.

A data acquisition and control system has been developed based on National Instruments' PXI hardware and LabVIEW software. Stand-alone program modules have been written to evaluate sensor performance, to conduct the permeability experiments, to analyze the collected data and calculate permeability value, and to review the experiment at reduced speed. The modules that monitor the sensors have been developed for both conductor and thermocouple-based sensors. An example of the real-time display is shown in Figure 8.

An analysis module that takes the elliptical flow front and calculates the in-plane components of the permeability sensor has been developed from expressions provided by Prof. Parnas. Full characterization of the analysis module is now underway following resolution of sensor reliability and accuracy issues.

A through-thickness rig has also been designed and fabrication of most hardware is underway as a lower priority task. Maximum pressure and viscosity are the same as the in-plane rig. The through-thickness rig has a flow capacity of 8 gpm. Through incorporation of a dynamic seal, preform thickness can be changed quickly for successive measurements to evaluate the influence of fiber volume fraction on permeability. This system will be completed and demonstrated as personnel and budgetary resources allow.

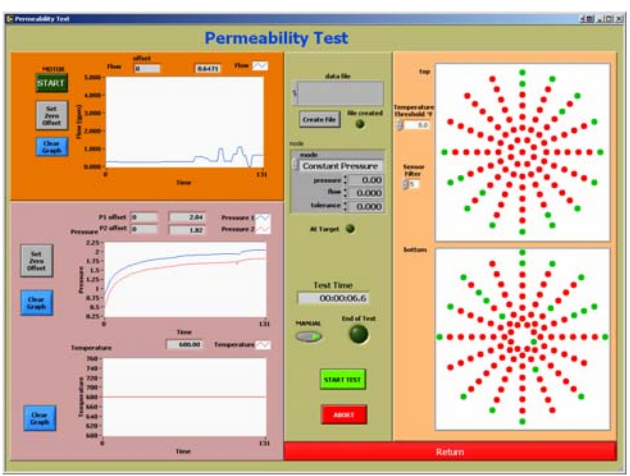

Figure 8. Permeability Test Rig Display showing radial progression of flow front indicated by a change in dot color.

Modeling of Fiber Deposition

A C-based program is under development to analyze the effect of process variables on preform characteristics. The program, FNSim, will be used to evaluate preforms in terms of measures such as fiber run length, fiber connectivity, distribution of voids, etc. FNSim, when correlated with permeability data and areal density measurements, will provide an understanding of the effect of process variables on resulting preforms and their "moldability." Recent advancements to FNSim have included efficiency improvements such that it now can be used on desktop computers as well as enhancement of the previously developed general modeling approach by addition or improvement of many of the capabilities. Examples of these enhancements include a new algorithm that makes quick simulation of tens of thousands of fibers possible, new algorithms for fast void discovery, an initial model for shaped substrate, and an initial model for mat compression. Further development of the model will be continued as program data is available to support model expansion and verification.

Fiber-Severing Technology

Due to significant differences in the physical properties of various reinforcement fibers as well as their available product forms, chopping technology that has been successful for glass fibers systems has demonstrated less-satisfactory results for the carbon-fiber products that are currently available. It is expected that similar results will occur for reinforced thermoplastics and hybrid glass-carbon products. Accordingly, consideration is given in this project to identifying alternative severing technology. A literature and patent search was undertaken to assess promising technologies for bench-top investigation. Possibilities identified include mechanical-based, laser-based, CO_2 pellet, liquid nitrogen, water-jet, and ultrasonic. Based on the information available in the literature and consideration of project team experience in related activities, laser-based choppers appear to offer the most promise.

During this period, effort was initiated to identify equipment and supporting tasks necessary to evaluate and demonstrate the potential for laser severing. Plans are under development to set up a laser system in the laboratory and experiment with a carbon-fiber tow at the bench scale to define the more detailed laser parameter and control requirements in order to be able to cleanly sever a moving carbon-fiber tow at the speeds required for utilization in the P4 system. Initial work will be done in static tests to determine beam width, power levels versus time, and other necessary information before moving to low speed tests, and then tests at speeds more representative of actual fiber deposition rates. With this background, plans are then to scale up the hardware for on-machine experimentation and demonstration. In addition to severing carbon fiber, future work will address other reinforcing fibers, as well as fibers used as binders, and blends of reinforcing and binder fibers.

Summary

A new project to develop the next-generation programmable preforming process and provide supporting technology to existing performing developmental work was initiated in FY 2004. The research will continue to build on past development and application of directed-fiber preforming processes, namely those of the Programmable Powdered Preform Process (P4), to extend the process to new material systems. Developments are expected to facilitate the use of low-cost carbon fiber, reinforced thermoplastics, and glass-carbon hybrid materials as effectively as is the current state-of-the-art with glass. Utilizing these materials is expected to lead to further reductions in vehicle mass in a more cost-competitive scenario than is currently possible. A preforming system, which will serve as the base for hardware and associated technology developments, was completed and installed in the polymer composites laboratories at Oak Ridge National Laboratory in the second quarter of FY 2005.

The base system is designed around glass-fiber product forms. A literature review has identified alternate severing technologies that may prove more effective for "chopping" the carbon, reinforced thermoplastics, and glass-carbon hybrids under investigation in this effort. During this period, effort was initiated to identify equipment and supporting tasks necessary to evaluate and demonstrate the potential for laser severing.

Efforts are underway to procure the most appropriate press, mold, and injection equipment necessary to demonstrate the advances achieved in performing technology through actual experimental composite manufacturing. ORNL staff has worked with members of the Automotive Composites Consortium's Processing Group to quantify process equipment requirements and write specifications necessary to procure this equipment that will allow ORNL to demonstrate preform advances while further investigating advances in the various molding processes themselves. At the time of this report, evaluation of the bid packages is being completed in order to get the equipment on contract in early FY 2006. Delivery of the experimental mold is anticipated in the second quarter of FY 2006 while delivery and final acceptance of the press is anticipated for the fourth quarter of FY 2006.

Development continued on two novel permeability rigs designed to characterize the preforms' resistance to resin flow during the molding process. The in-plane rig has been constructed and experiments initiated. Issues with initially-provided conductive-sensor reliability and accuracy have been identified, and appear to have been resolved with development and implementation of an entirely new temperature-based sensor concept. The through-thickness rig has been designed and hardware components purchased. A data acquisition, control, and analysis system is continuing to be implemented and fine-tuned for the radial rig and will be used in completion and troubleshooting experiments with the through-thickness rig. Together, the two rigs will provide the three-dimensional permeability data for the comparison of preformed materials as well as development of mold-flow models.

Modeling of the fiber deposition process continues at a low level through the development of an in-house code. The program, FNSim, will be used to evaluate preforms in terms of measures such as fiber run length, fiber connectivity, distribution of voids, etc. Results will be correlated with permeability data and areal density data to assess the affect of process parameters on preform quality as well as the mechanical properties of molded parts.
Collectively, the technology under development in this project will advance low-cost processing on two fronts. First, it will provide the opportunity to

employ additional materials in the net-shape preforming process, which is expected to lead to additional mass reduction and/or better performance. Second, it will provide the requisite tools to evaluate the affect of process parameters on the utility and performance of preforms and molded parts.