

## 4. POLYMER COMPOSITES R&D

### A. Development of Manufacturing Methods for Fiber Preforms (ACC 040<sup>i</sup>)

*Principal Investigator: Patrick Blanchard*

*Ford Motor Company, Research and Innovation Center*

*P.O. Box 2053, MD 3135 RIC, Dearborn, MI 48121-2053*

*(313) 390-6230; fax: (313) 390-0514; e-mail: pblanch3@ford.com*

*Principal Investigator: Jeff Dahl*

*Ford Motor Company, Research and Innovation Center*

*P.O. Box 2053, MD 3135 RIC, Dearborn, MI 48121-2053*

*(313) 845-1039; fax: (313) 390-0514; e-mail: jdahl@ford.com*

*Project Manager: C. David Warren*

*Oak Ridge National Laboratory (ORNL)*

*P.O. Box 2009, Oak Ridge, TN 37831-8050*

*(865) 574-9693; fax: (865) 574-0740; 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*

*Expert Technical Monitor: Philip S. Sklad*

*(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov*

---

*Contractor: U.S. Automotive Materials Partnership*

*Contract No.: DE-FC05-95OR22910*

---

#### Objective

- Develop and demonstrate new fiber-preforming processes to decrease cost, increase manufacturing rates and improve reproducibility of large preforms for composite molding.
- Develop the thermoplastic programmable powdered preform process (TP-P4) concept as a high-volume composite manufacturing process for thermoplastic composite materials.
- Develop low-cost carbon-fiber rovings with reduced individual bundle size.

#### Approach

- Investigate materials, process equipment, and tooling technology to further reduce the cost and enhance the quality of chopped-fiber preforms.
- Explore the extension of automated preforming technology to make preforms with a thermoplastic matrix.
- Investigate heating methods for thermoplastic composite blanks manufactured using the TP-P4 process.
- Perform cost analysis to determine the economic benefits of the TP-P4 process technology.

#### Accomplishments

- Completed preliminary processing studies to establish feasibility of the TP-P4 process.
- Completed a business assessment of the TP-P4 process technology.

## Future Direction

- Further develop P4 process technology to accommodate rapid cycle times in support of high-volume production.
- Continue cost modeling of process concepts to determine business rationale for migration of process technology to the OEM supply base.

## Introduction

This project has focused on the development of the P4 process, a fully-automated robotic preforming process. A prototype, two-station manufacturing cell was designed, fabricated and installed at the National Composites Center (NCC) in Kettering, Ohio. This equipment is currently being utilized to support preforming and material development efforts within the Automotive Composites Consortium (ACC).

During this reporting period, the facilities at NCC were used primarily in support of new process developments for a derivative of the conventional P4 process. The new process makes use of commingled yarn for subsequent hot-flow compression molding. Preliminary investigations were conducted to determine the feasibility of the process. The sections that follow, describe the results from these studies.

### Thermoplastic P4 (TP-P4)

**Equipment Capability:** The existing P4 processing equipment, originally designed for preforming of glass fiber materials, has been adapted to enable manufacture of thermoplastic composites. However, the capability of this equipment is limited in terms of cycle time and hence throughput capacity. Regardless of these limitations, processing parameters have been developed to allow manufacture of components in the order of 700 mm x 700 mm, while maintaining minimal process interruptions. Process yield, measured by part weight, is currently 1500 g/min, although attempts have been made to increase this to 5000g/min. However, from a commercial perspective the low material output would ultimately lead to increased capital investment for high-volume production. By way of example, for a vehicle liftgate panel, the cell will currently support 1 part every 7.5 minutes. If the target cycle time for this component is 45 s, this translates to either 10 lines of process equipment or a ten-fold increase in material throughput capability

for a single cell. This prompted a re-design of the cell with the objective of accommodating the higher throughput capabilities.

As part of the design process, a manufacturing cell layout was developed for production of the liftgate inner panel described above. Process simulation software was used to account for the dynamics of the process and resultant cycle times. The surface area of the liftgate was calculated as 1.5 m<sup>2</sup>. All analyses were conducted assuming a final part thickness of 3.0 mm with an areal density of 4500 g/m<sup>2</sup>.

From the process simulation studies, the following conclusions can be made:

- For a 1.5 m<sup>2</sup> part surface area, a 45 s cycle time is achievable from a single cell.
- Material throughput for the TP-P4 cell would need to be capable of 20 kg/min to meet the target cycle time.

Based upon these results, a more detailed cell specification has been developed. Several equipment manufacturers have also been contacted regarding the feasibility of designing and building a unit to meet these specifications.

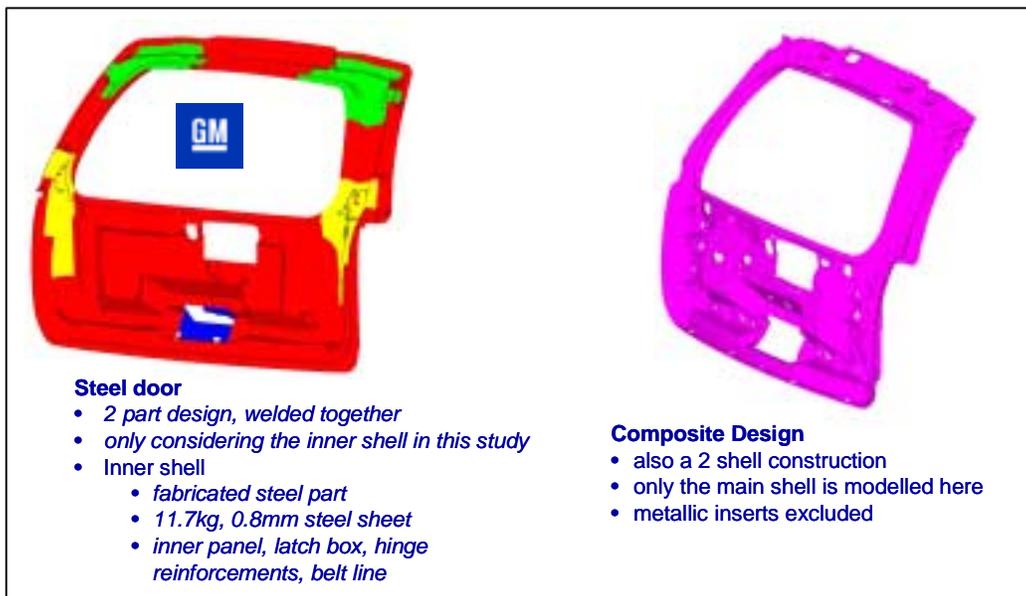
**TP-P4 Tooling:** Experimental studies to date have been conducted on an existing flat-panel tool (700 mm x 700 mm). The size of this tooling limits the size of parts used for basic material characterization and process development. Therefore, a new tool, measuring 1500 mm x 2250 mm, has been designed for larger components. This tool will allow development of thermoplastic composite components such as the liftgate inner panel. It will also be used for extended testing of TP-P4 manufacturing cell to validate process robustness. Fabrication of this was completed in quarter four (Q4) of 2006.

**TP-P4 Process Cost Modeling:** To evaluate the economic merits of the TP-P4 process technology, a cost modeling contract was awarded to the EPFL in Lausanne Switzerland. The statement of work developed included a comparison with competing composites-based processes. In total, seven different competing technologies were compared to the TP-P4 option and its derivatives. Table 1 provides a summary of the conventional process technologies that were compared to a proposed TP-P4 manufacturing cell. In parallel to identification of competing process technology, target applications were selected in order to establish the complete

manufacturing process. Two components were selected: a liftgate inner, based upon a concept developed for a General Motors (GM) sport utility vehicle; and a rear seat frame from a Chrysler minivan. It was anticipated that the size and complexity differences for these parts would yield an insight into the suitability of the TP-P4 process for a broad range of components. However, this report provides a summary restricted to the liftgate analysis as the seat-back modeling remains on-going. A computer-assisted design (CAD) rendering of the liftgate geometry is shown in Figure 1.

**Table 1.** Process comparison used to evaluate the thermoplastic P4 process.

Conventional Composites Technology
Direct LFT Injection
Indirect LFT Injection
Direct LFT Compression
GMT Compression
GMTex compression
<i>Hybrids</i>
Direct LFT Compression + fabric over-molding
Direct LFT Injection + fabric over molding



**Figure 1.** CAD rendering of steel liftgate and composite concept.

Based upon the intrinsic material properties and individual process characteristics, mass assumptions were developed for the different composite options. As material price is typically a major contributor to overall piece price, considerable effort was made to assign realistic targets for each process. However, as the scope of the cost analysis was limited to a screening study, no structural analyses were performed. For example, the part manufactured in glass mat thermoplastic (GMT) was assumed to weigh 6.6 kg, whereas further weight reductions were forecast based upon the increased fiber loading

(60% wt vs. 40% wt) offered by the TP-P4 manufacturing route. This resulted in an assumed part mass of 5.1 kg. Table 2 also describes the effect of hybrid processing on part mass. In these cases, processes were combined to allow over-molding of structural composite inserts. The columns labeled “upper” and “lower” indicate the limits applied to sensitivity analysis; however, this detail is not included in this report. Once the process options and part dimensions had been defined, process layouts were developed for each cost analysis.

**Table 2.** Dimension and mass assumptions of liftgate designs.

<b>Lift gate</b>			
part X,Y, Z (for machine bed size etc)	<b>1.5m width, 1.1m high, 250mm deep</b>		
part projected area (for tonnage calculations)			
max part thickness	<b>5mm</b>		
min part thickness	<b>3mm, 2.5mm ribs</b>		
ribs	<b>2.5mm</b>		
<b>Weight assumptions, (kg)</b>	baseline	upper	lower
Part mass in steel	<b>11.7</b>		
Part mass in GMT	<b>6.6</b>	<b>6.7</b>	<b>6.5</b>
Part mass in GMTex 4-1/GMT	<b>6.2</b>	<b>6.6</b>	<b>6.0</b>
Part mass in TP-P4 random 60% gf	<b>5.1</b>	<b>5.2</b>	<b>5.0</b>
Part mass in TP-P4 random 60% gf + GF/PP 40 LFT hybrid	<b>5.1</b>	<b>5.8</b>	<b>5.1</b>
Part mass in TP-P4 random 40% gf	<b>6.6</b>	<b>6.7</b>	<b>6.4</b>
Part mass in GF/PP 50 celestran (IM)	<b>6.4</b>	<b>6.6</b>	<b>6.3</b>
Part mass in GF/PP 40 direct LFT	<b>6.6</b>	<b>6.7</b>	<b>6.5</b>
Part mass in Tw-40 indirect	<b>6.6</b>	<b>6.7</b>	<b>6.5</b>
Part mass in Twintex 4/1 fabric + GF/PP 40 LFT hybrid	<b>5.0</b>	<b>5.1</b>	<b>4.9</b>

In summary, the analysis suggests that for large components that do not require the strength and modulus benefits of TP-P4, either of the direct-feed processes will offer a cost advantage. However, the potential weight savings may still remains a key consideration. In cases where typical direct long-fiber thermoplastic (D-LFT) injection or compression properties are insufficient, the TP-P4 process can be combined as a hybrid process to offer a low-cost and lightweight solution. Furthermore, for structural parts that typically require GMT materials, the TP-P4 option is considered a cheaper and lighter alternative.

It should be noted, that while the above analysis justifies continued research into TP-P4 process development, several basic process assumptions need to be demonstrated. In particular, technical feasibility of the high-throughput TP-P4 cell has still to be proven. Furthermore, final selection of an

appropriate heating method for TP-P4 materials is still outstanding. Therefore, while the future TP-P4 process capabilities that were included in the model are considered realistic, considerable technical work is required to develop a robust and repeatable process.

**TP-P4 Materials Characterization:** A series of specimens was extracted from 18" x 18" flat plaques manufactured using the TP-P4 process. The main objective of this exercise was to establish baseline performance as a reference to determine future improvements in materials performance.

**Tensile Specimens:** Procedures listed in ASTM D638 were followed in fabricating the tensile specimens, which were 216 mm (8.5 inch) in length and 19mm (.75 inch) wide. The “neck down” region was 12.7 mm (.50 inch) wide at the center. Specimens were sectioned by using a diamond-blade

band saw, while the “necked down” region was milled using a high-speed router. Fine filling was used to reduce potential stress risers that could influence specimen data. All tensile specimens were tested on an MTS Sintech 30/G load frame with a Renew™ interface Works 4.0 data acquisition software. A 30,000 lb. load cell was calibrated and used in conjunction with a two-inch longitudinal extensometer.

**Compression Specimens:** Procedures listed in the ASTM D3410 were followed in fabricating the compression specimens, which were 127 mm (5.0 inch) in length and 12.7 mm (.5 inch) wide. The specimens were sectioned using a diamond-blade band saw. Fine filling was used to reduce potential stress risers that could influence specimen data. All compression specimens were tested on an MTS 810 load frame and microconsole with Test Works 2.1 data acquisition software. A 10,000 lb. load-cell cartridge was used in conjunction with a 5.0-inch-stroke cartridge. The Ford Motor Company version of the standard IITRI lock-down compression fixture was used for testing.

**Flexural Specimens:** Procedures listed in the ASTM D790 were followed in fabricating flexural test specimens, which were 127 mm (5.0 inch) in length and 25 mm (1.0 inch) wide. The specimens were

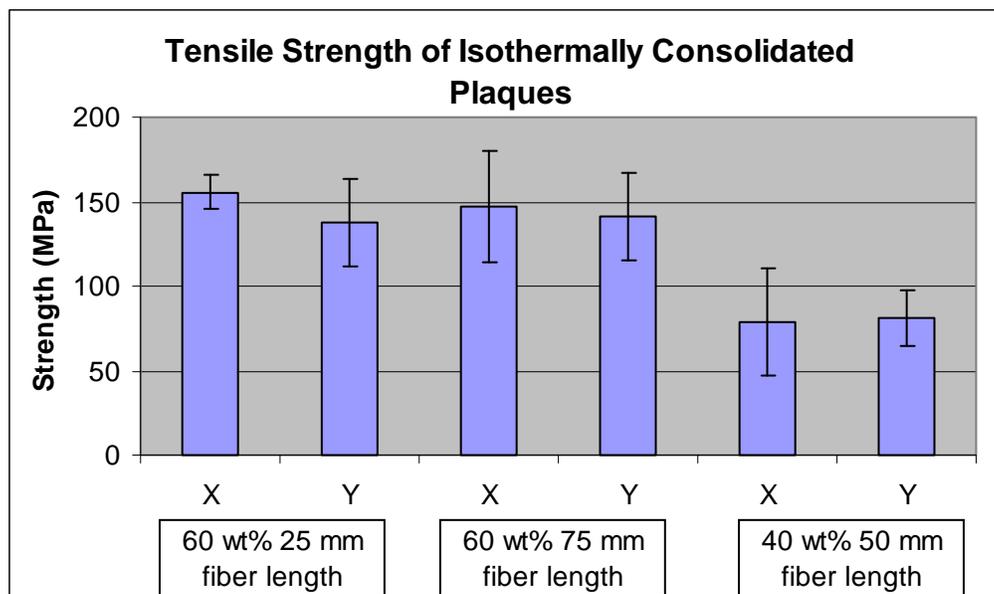
sectioned using a diamond-blade saw. Fine filling was used to reduce potential stress risers that could influence specimen data.

### Results

Property measurements of TP-P4 blanks are shown in Figures 3 to 7. These values appear to be in line with other commercial alternatives. However, a further series of tests will be performed to determine any additional benefit to the retention of fiber length in process blanks. At present, blanks have been processed using 75-mm-long fibers, which is an order of magnitude higher than other compression-molding processes.

### TP-P4 Preheating Studies

The TP-P4 process can result in a lofted composite charge that exhibits some rigidity and handling strength. However, under these circumstances, the heating cycle within the TP-P4 process is often insufficient to create good wetting of the fiber reinforcement bundles and overall charge consolidation. This presents a new challenge regarding establishing a suitable means of heating the TP-P4 material prior to molding. Hence, a series of investigations was conducted on materials processed under a wide variety of process conditions using infrared (IR), forced-air and convection ovens.



**Figure 3.** Tensile test results for isothermally-consolidated TP-P4 blanks.

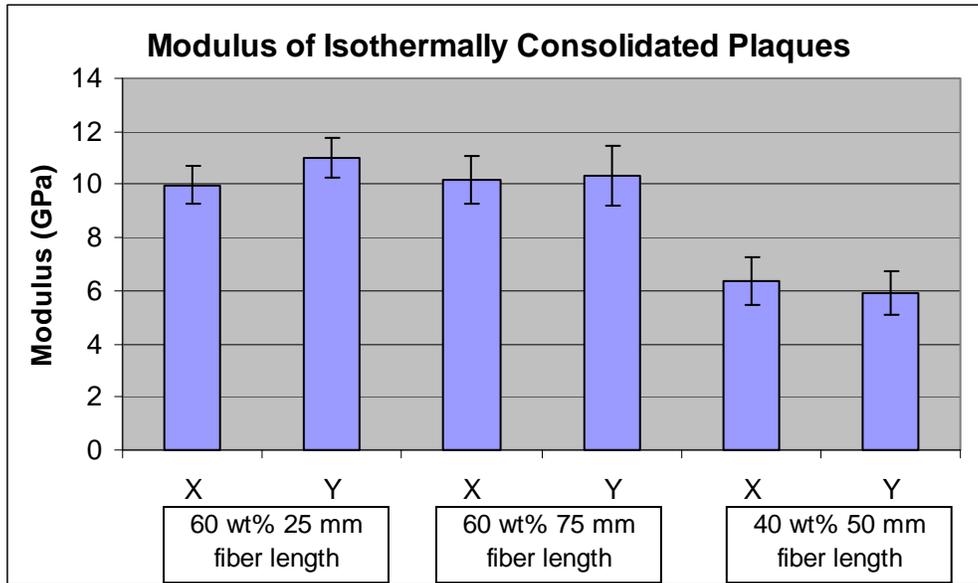


Figure 4. Tensile modulus results for isothermally-consolidated TP-P4 blanks.

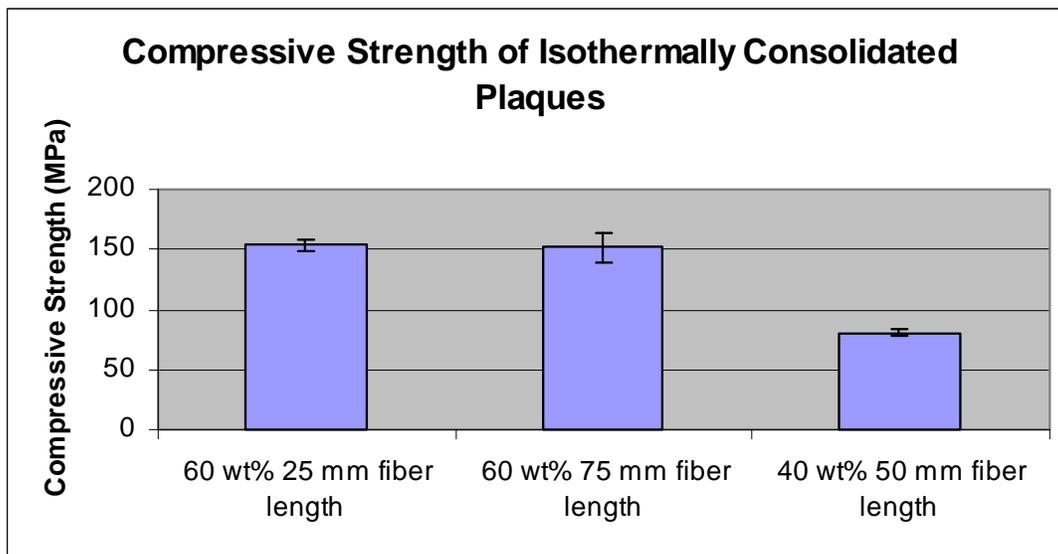
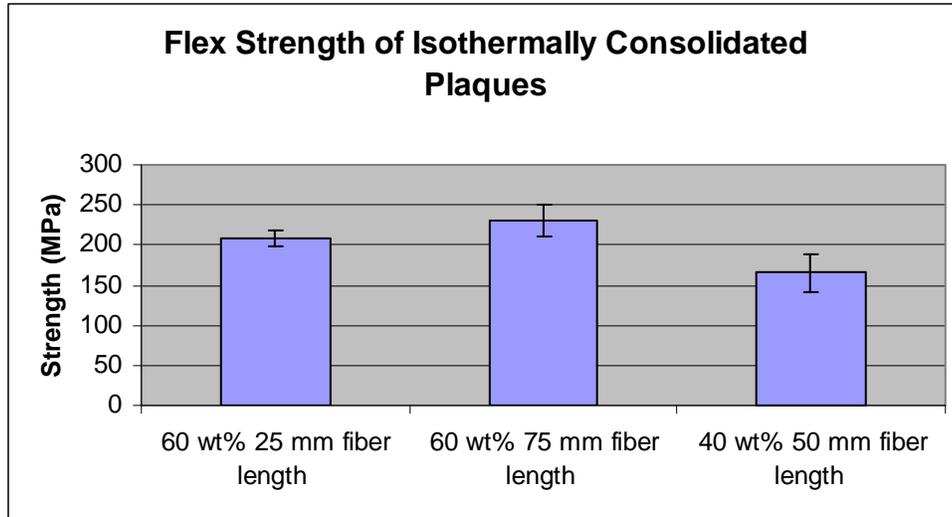


Figure 5. Compressive strength test results for isothermally-consolidated TP-P4 blanks.

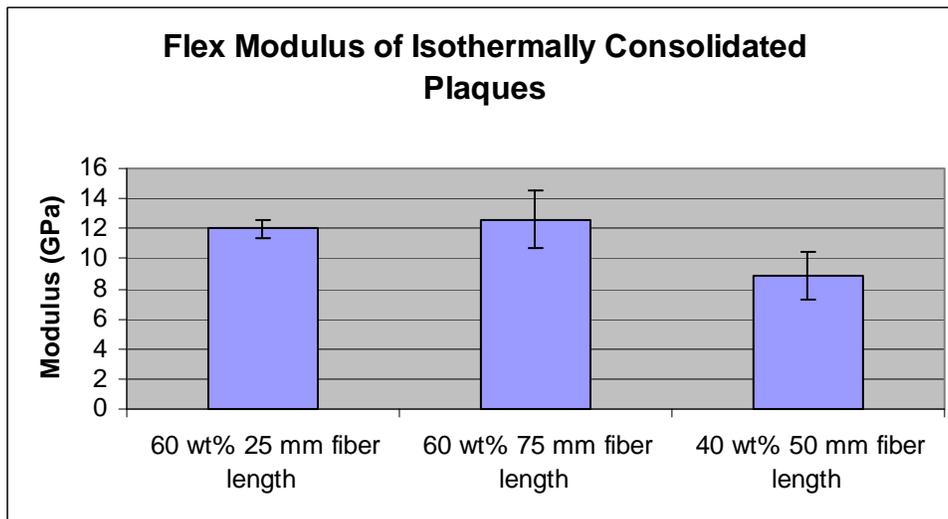
The main objective of the study was to determine the most appropriate material form and heating method for TP-P4 materials processed under different conditions.

**Experimental Methods:** Heating studies were performed on TP-P4 materials processed to a range of consolidation levels.

TP-P4 blanks of ~50% void content were heated with an IR oven to determine optimum time and temperature profiles for future design-of-experiment (DoE) studies. The heated samples were nominally 100 mm wide and 381 mm long. Low-porosity samples (< 5%) of thickness 3.5, 4, 5 and 6 mm were also examined. The samples were fitted with three J-type thermocouples positioned approximately at the center of thickness. Temperature histories were recorded



**Figure 6.** Flexural strength test results for isothermally-consolidated TP-P4 blanks.



**Figure 7.** Flexural modulus test results for isothermally-consolidated TP-P4 blanks.

during heating trials to determine the heat-up rates of materials in either a consolidated or unconsolidated state.

**Sample Manufacture:** The TP-P4 materials were comprised of 60% wt. fiberglass and 40% wt. polypropylene (PP), and manufactured using equipment installed at the NCC.

**Preheating Options:** Several preheating options were identified such as a free convection, infrared (IR) and forced-air convection.

Free-convection studies were performed using a Fisher Scientific- ISOTEMP® 800 Series, model 13-247-838F (medium) oven. It provides a temperature range from 50°C to 325°C in 1°C intervals. A small ventilator made the temperature relatively uniform in the oven, but did not give extensive air circulation.

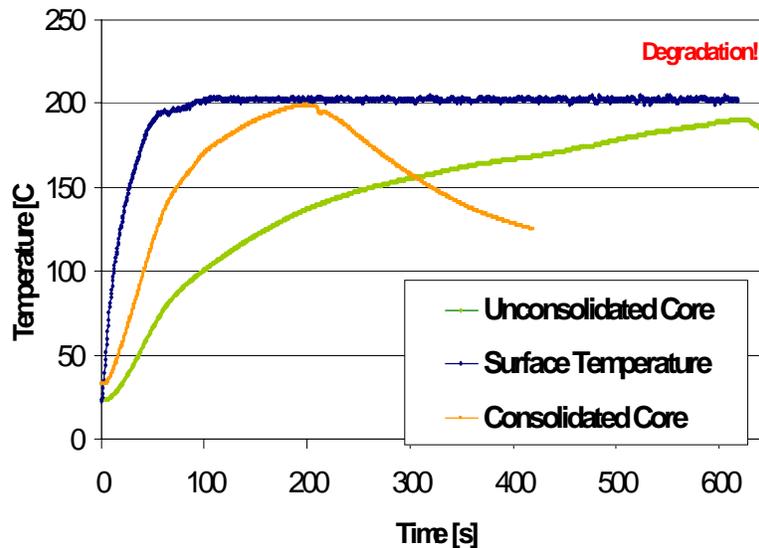
The RR-heating studies were performed using a Krelus IR-heating oven with six upper zones and six lower zones, each individually controlled. Each zone contains 2kW, 9.1A IR medium wave units. The forced-air preheating study was performed with an Ernst Reinhardt GmbH, forced-air convection oven

based at the EPFL. The following parameters were used:

- convection: 45m<sup>3</sup>/min
- 2m<sup>3</sup> operating volume
- oscillating tray (for more homogeneous preheating)
- oven set temperature: 230°C

**Results and Discussion**

For materials consolidated to a porosity level of approximately 43%, rapid heating of the material could be achieved. Hence, there appeared to be no further benefit to creating material blanks of increased consolidation. However, unconsolidated blanks were more difficult to heat as highlighted in Figure 8.



**Figure 8.** Comparison of core temperatures for unconsolidated and consolidated 3.5 mm blank (202°C setpoint).

Although a free-convection oven is a low-flux density method of heating, as opposed to IR heating, degradation was observed in all TP-P4 samples tested in this oven because of the

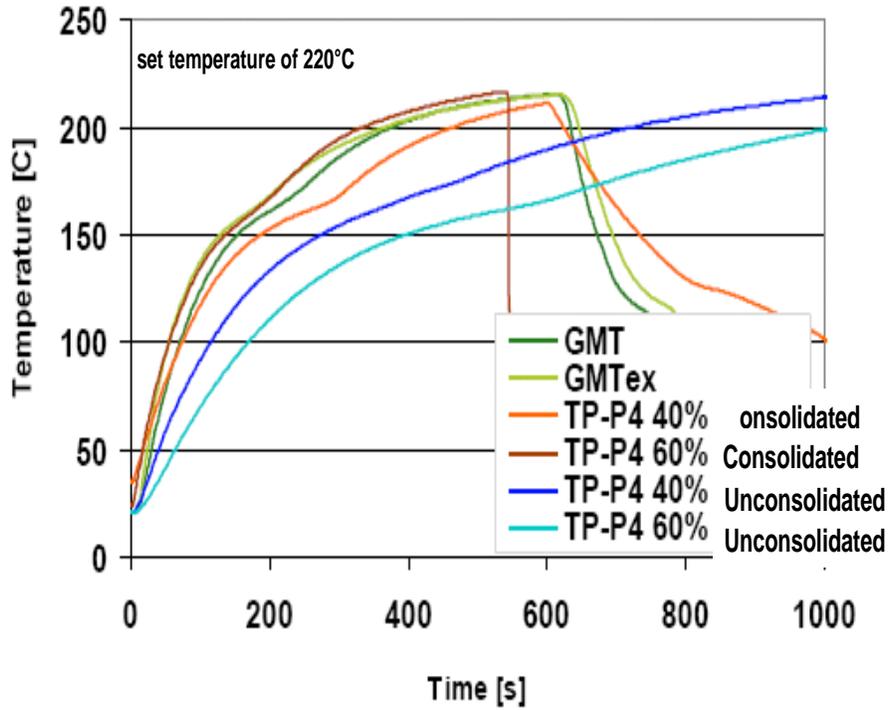
extended heating times required. Comparisons between unconsolidated and consolidated heating curves in a free-convection oven can be seen in Figure 9.

Figures 10 and 11 show that rapid heating can be achieved using the forced-air oven. For these tests, 2 mm blanks were heated to 180°C within 2.1 to 2.3 minutes whether using consolidated or unconsolidated blanks. However, as Figure 12 and 13 indicate, with thicker blanks such as 6 mm, the differences in heating times are significant between unconsolidated and consolidated blanks. The cores of unconsolidated 6 mm blanks heated to 180°C in 16.5 minutes compared to 14.8 minutes for consolidated blanks. In summary, the difference between heating times for cores of blanks thicker

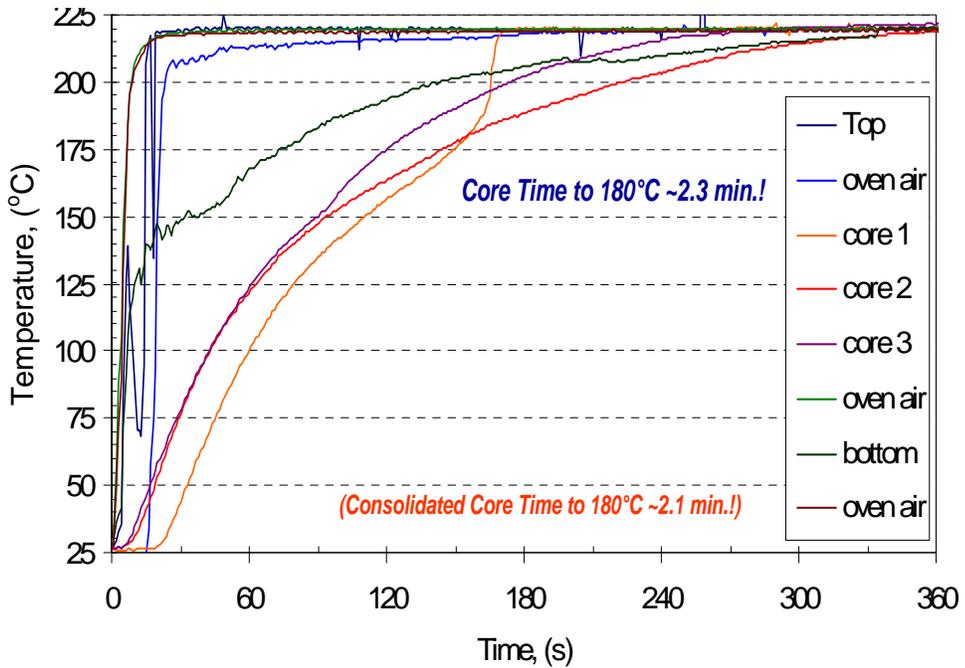
than 4 mm are greater than those of thinner blanks. However, the likelihood of needing to heat blanks of such thickness is remote. The results do prove that thinner blanks, such as 2 mm, can be heated in forced-air ovens without first being consolidated. Such practice would eliminate the need for any consolidation equipment and associated costs.

**Conclusions**

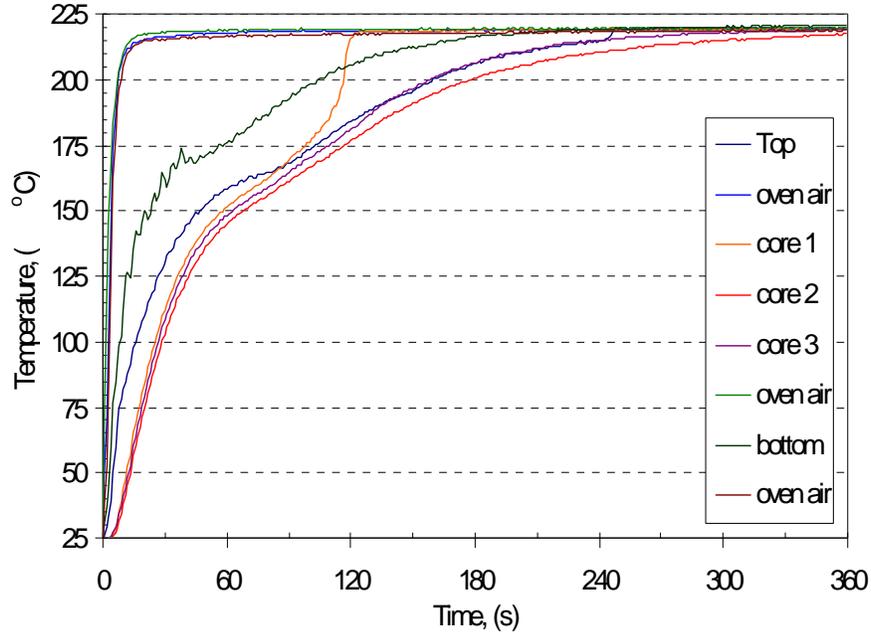
In conclusion, the forced-air convection oven provides the most optimum heating environment to heat TP-P4 blanks. This conclusion is based upon reduced material degradation while maintaining rapid heating times. Although IR ovens are commonly used to preheat thermoplastic material blanks, there is increasing interest and use of forced-air and impingement ovens as their surface flux levels are much lower and they exhibit increased uniformity of heat. In practice, it may be optimum to heat TP-P4 materials in a combination IR/forced-air



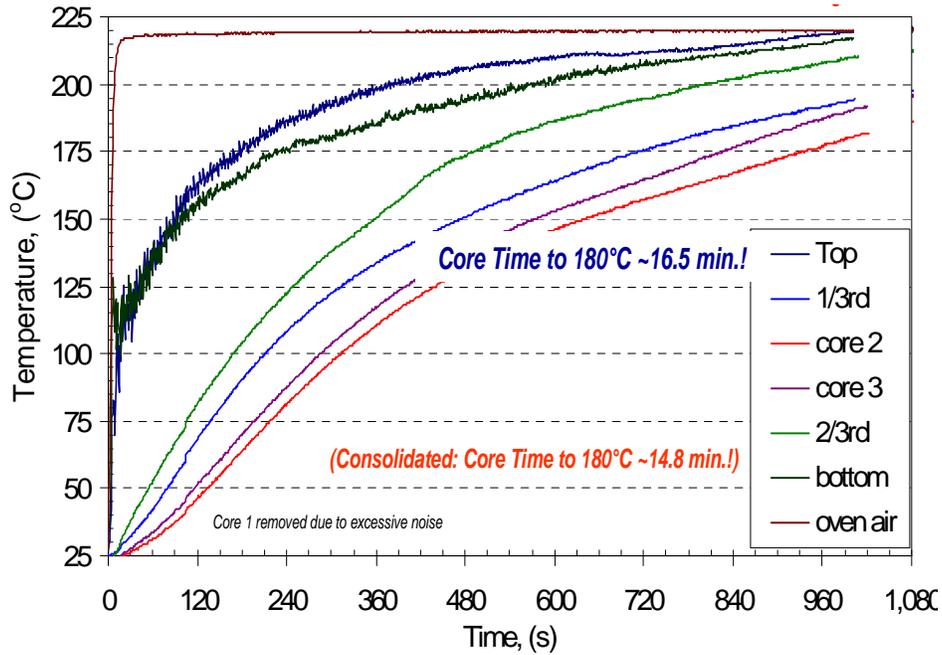
**Figure 9.** Temperature histories of unconsolidated and consolidated blanks heated in a free-convection oven (standard GMT is included as a comparison).



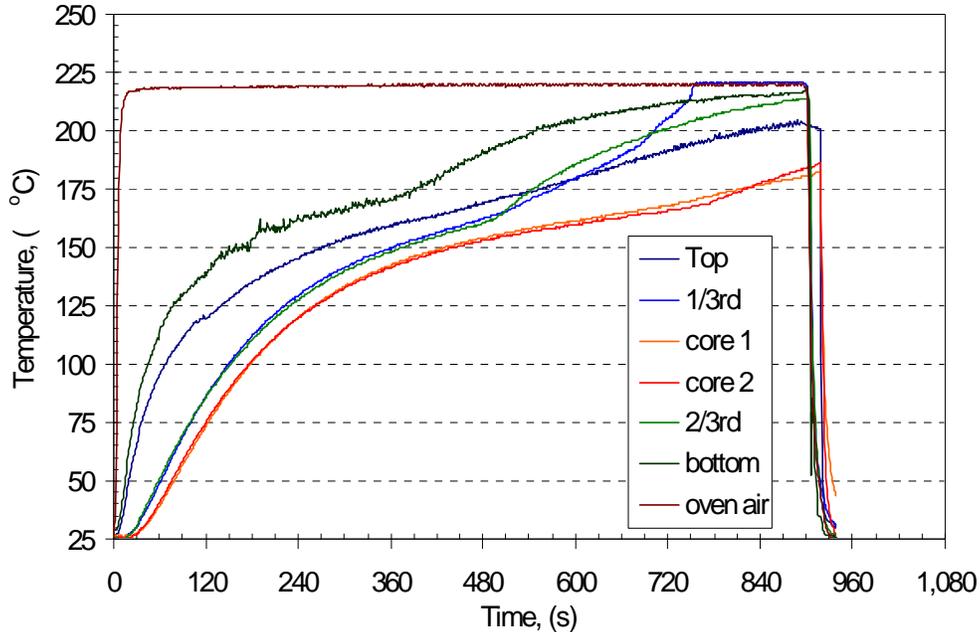
**Figure 10.** Temperature histories for unconsolidated 2 mm sample (forced-air oven, 220°C, 50% fan speed).



**Figure 11.** Temperature histories for consolidated 2 mm sample (forced-air oven, 220°C, 50% fan speed).



**Figure 12.** Temperature histories for unconsolidated 6 mm sample (forced-air oven, 220°C, 50% fan speed).



**Figure 13.** Temperature histories for consolidated 6 mm sample (forced-air oven, 220°C, 50% fan speed).

oven, such as an indexing conveyor type oven with an initial IR-heating station which then indexes the blank into a pressure-differential type forced-air oven until the core temperature is achieved.

Free-convection ovens are not feasible for production of unconsolidated or consolidated blanks due to the excessive time at temperature causing significant degradation to the surfaces before the core reached a set temperature.

If an upper limit of blank thickness is set to 2 mm thickness or less, it appears that a forced-air oven works well and that the level of blank consolidation does not inhibit heating rates.

### **Carbon-Fiber Roving Development - Toho Tenax Carbon Fibers**

The research program with Toho Tenax to develop carbon fiber rovings more amenable to the P4 preforming process has been terminated. Toho Tenax was unwilling to continue with this research program.

---

<sup>i</sup> Denotes project 040 of the Automotive Composites Consortium (ACC), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development.