

Microwave-Assisted Plasma Carbon Fiber Manufacturing



2001 R&D 100 Award Entry Form

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Submitter's signature _____

2. **Joint submitter**

Not applicable.

3. **Product name:**

Microwave-Assisted Plasma (MAP) Carbon Fiber Manufacturing Process

4. **Product description**

The Oak Ridge National Laboratory (ORNL) Microwave-Assisted Plasma (MAP) Carbon Fiber Manufacturing Process is a revolutionary technology for carbonizing and graphitizing carbon fibers at much higher speeds and significantly lower costs than those achievable by present industrial practice. Carbon fibers are in demand for a growing number of applications, in industries ranging from aerospace to sporting goods. Use in some products is currently prohibited because of limited availability and high cost. The automotive industry, in particular, will benefit from a cheap, abundant source of carbon fiber.

^a Research sponsored by the U.S. Department of Energy and performed at Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725. The submitted manuscript has been authored by a contractor of the U.S. government under contract No. DE-AC05-00OR22725. Accordingly, the U.S. government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. government purposes.

5. Eligibility

This product was first marketed/available for order:

The MAP carbon fiber manufacturing process became commercially available during CY 2000, when it met and exceeded targets established by ORNL in partnership with the U.S. Council for Automotive Research. Members of the carbon fiber industry have been briefed periodically on progress in this project and have expressed interest in commercializing the MAP process when target process, property, and economic parameters have been demonstrated. Now that this milestone has been achieved, active marketing of MAP technology is under way with the intention of establishing widespread commercial utilization and thus enhancing the U.S. competitive position in the composites industry. (See confirmation letters in Attachment A.)

6. Inventor or principal investigator

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7. Product price

NOTE: Precise licensing costs for the MAP carbon fiber manufacturing technology and details of its effect on the cost of carbon fiber products are proprietary. Cost models developed by ORNL and the Massachusetts Institute of Technology with the concurrence of carbon fiber producers indicate that MAP technology should result in a reduction in product cost of about 20% in commercial-grade carbon fibers ^a (e.g., \$6.50/lb vs the current cost of \$8.00/lb). This makes carbon fiber structural materials much more attractive to the vast and highly cost-competitive automotive market. The estimated cost impact on various production stages is shown in the following table. Note that the cost of carbonization and graphitization are both reduced by at least 50%, with a total cost reduction of approximately 20%.

Comparison of Carbon Fiber Cost by Stage of Production

Process Step	Conventional (\$/lb. of Output)	MAP (\$/lb. of Output)	% Change
Pretreatment ^b	3.88	3.78	-2.6
Oxidation	1.34	1.09	-18.7
Carbonization	1.00	0.50	-50.0
Graphitization	1.19	0.50	-58.0
Surface Treatment ^c	0.18	0.19	5.6
Sizing	0.16	0.15	-6.3
Materials Handling	0.22	0.21	-4.5
Inspection & Building	0.32	0.28	-12.5
Total	8.30	6.70	-19.3

^b Pretreatment contains the raw material cost.

^c Conventional surface treatment contains a low cost dryer whereas fourteen –6kW ovens are required with microwave processing.

Base:

Carbon fiber production volume: 2.2 million lbs/year.

50K or 60K PAN based tows.

^a A Cost Assessment of PAN Carbon Fiber Production Technologies: Conventional and Microwave Cases. S. M. Cohn and S. Das, ORNL report, Feb. 1999.

8. Patent information

- a. Patents held Yes _____ No X
- b. Patents pending Yes X No
- c. Patents held by others Yes _____ No X

Domestic and foreign patents are pending for the MAP carbon fiber manufacturing process and for related technology developed by ORNL that will allow further improvements to product quality and reductions in cost.

9. Function

The carbon fiber industry uses the terms carbon fiber and graphite fiber interchangeably; in fact, all carbon fiber contains some graphite. Commercial carbon and graphite fibers are currently produced through the controlled heating of bundles of straight filaments (tows) of fibrous organic carbon precursors such as polyacrylonitrile, pitch (petroleum or coal tar), or rayon. The PAN precursor tow undergoes stabilization and oxidation in air up to approximately 250 °C. Subsequently, the stabilized tow is fired in an inert atmosphere at extremely high temperatures between 1000 and 2000°C, while under slight tension. The fibers undergo pyrolysis, during which organic material converts into carbon, and noncarbon elements are expelled in the form of volatile gases. The entire carbonization step, a lengthy and expensive process, is typically performed in one or more conventional graphite-brick-lined furnaces and requires several hours to complete.

The MAP carbon fiber manufacturing process developed at ORNL uses plasma technology and microwave radiation to produce carbon and/or graphite fibers. (See the illustrations in Attachment B.) A stabilized precursor tow is placed in an oxygen-free atmosphere, under slight tension, and is subjected to increasing levels of plasma energy and microwave radiation as it progresses toward a final carbon or graphite product. The apparatus is modular and much smaller than conventional carbonizing furnaces. The plasma is generated in a tightly controlled oxygen-free plasma chamber. An inert gas purges the system of oxygen and acts as a carrier for the effluents generated by the process. The microwave radiation is generated by a standard microwave generator, capable of providing radiation in the range of 915 to 2450 MHz.

We believe that the carbon fiber precursor is processed by a variety of different and complex mechanisms during the MAP process. First, most of the microwave energy couples directly to the

plasma, which in turn produces a flux of electrons, ions, neutral free radicals, and ultraviolet radiation, all of which impinge on the surface of the tow filaments. The combined fluxes cause enhanced carbonization because their energies are many orders of magnitude higher than those of the ordinary thermal fluxes used in conventional processing. The high-energy fluxes break the chemical bonds in the complex organic molecules present in the filaments, thus enhancing the release of gases.

Carbon is an ideal microwave absorber, and the microwave energy that did not couple with the plasma is absorbed directly by the carbon, heating it directly. The microwaves are absorbed uniformly over the bulk of the tow cross-section because the absorption depth of the microwave energy is much greater than the tow diameter. The plasma and ultraviolet fluxes process the carbon fiber filament surfaces and thus, enhance the release of unwanted compounds (effluent gasses) from the filament surface. The released gases can be used to determine when carbonization is complete or whether an increase in the level of microwave energy is needed.

Untreated carbon and/or graphite fiber surfaces usually have low surface energies, which limit their ability to form strong adhesive bonds with matrix materials. Therefore, the surfaces of the fibers are treated to increase their surface activity and surface energy and thus enhance their ability to adhere to a matrix material, usually a polymeric resin. In conventional processing, a separate setup is required for surface-treating the fibers. In MAP processing, it can be done in the same processing line by carefully introducing oxygen into the chamber following completion of the carbonization process.

The MAP process also simplifies carbon fiber production by replacing both carbonization and graphitization processing steps with a single MAP processing step. Another major benefit is that the off-gases produced during the carbonization process supplement the plasma reaction and drive carbonization, thus reducing the amount of volatile gases in the effluent gas stream, which must be purified prior to venting.

10A. The competition

Note: All cost information for the MAP Carbon Fiber Manufacturing Process is proprietary.

The competition for the MAP Carbon Fiber Manufacturing Process is the current conventional thermal pyrolysis process for producing carbon fibers. The conventional process is very robust and has been the “workhorse” for this industry for many years. It is capable of producing a wide range of material

properties that can be tailored to meet customer needs; however, its high cost and slow processing times are the principal impediments to a much greater commercial use of carbon fiber. This technology is very mature, implying that changes would now be typically evolutionary and that cost reductions or product improvements would be incremental.

Currently, more than 30,000 tons of carbon fibers are produced annually throughout the world. Although this may seem to be a substantial amount, the commercial industry has yet to realize the potential widespread use of carbon fibers because they cost much more to produce than other materials. The most significant cost factors include the high cost of carbon precursors (45–50% of production costs), equipment and energy (20–25% of production costs). In addition, the methods currently used to produce a quality carbon fiber are time consuming; attempts to speed up the process have often resulted in the rapid burnoff of the noncarbon elements, causing bubbles and cracks in the fiber. The bubbles and cracks substantially weaken the mechanical properties of the fibers, making them unfit for their intended purpose.

MAP technology is revolutionary. It is significantly faster at generating materials comparable to those currently commercially available. Current estimates point to cost reductions of about 20% upon implementation of the MAP technology due to combinations of the greater line speed, lower energy use, lower capital equipment and space requirements, and greater production flexibility. In short, the MAP Carbon Fiber Manufacturing process is capable of providing equivalent or better products more quickly and with more flexibility *and at a significantly reduced cost.*

10B. Comparative matrix

	Conventional Process ^a	MAP Process ^b	PNGV Program Goals ^c	Advantages MAP vs. PNGV Program
Modulus ($\times 10^6$ lb/in. ²)	31.1	31.7	25	Stiffer
Ultimate stress ($\times 10^3$ lb/in. ²)	485.3	424.1	300	Stronger
Elongation at break (%)	1.5	1.3	1.0	More Deformable
Density (gm/cm ³)	1.77	1.83	N.A. ^d	
Calculated tow area ($\times 10^{-2}$ cm ²)	2.17	1.90	N.A. ^d	
Filament diameter (μ m)	7.43	6.97	N.A. ^d	
^a Assumes a typical 50,000-filament (50K) tow, such as Fortafil 3(C), which is representative of current commercial products. ^b Assumes a 50K tow. ^c Goals set by the Partnership for a New Generation of Vehicles (PNGV) in an effort to produce safer, more economical vehicles. ^d Not a specified PNGV requirement.				

10C. Improvements upon competitive products or technologies

Targets for specific carbon fiber properties were identified in collaboration with key automotive industry planners as criteria for widespread utilization of carbon fiber in the automotive industry (assuming significant cost reduction). A cost target for this process itself has not been identified, but a cost reduction of about 20% for this process has been estimated, based on economic model in section 7. The cost analysis was subsequently reviewed and validated by several carbon fiber manufacturers.

Electrical and mechanical properties as well as the morphology of carbon fibers produced by MAP processing are comparable to those in commercial 50,000-fiber (50K) tows presently on the market. (e.g., Fortafil 3[c]; See Attachment C for more extensive data on the electrical, mechanical, and morphological properties of the carbon fiber.)

The principal advantages of MAP processing are reduced costs and improved control over the fiber surface. Preliminary estimates indicate that MAP processing may result in a reduction of delivered carbon fiber costs by about 20%. This cost reduction is attributable to several technological features:

- faster processing speeds;
- reduced energy demand;
- reduced footprint (compact equipment and plant layout);
- reduced investment cost for both capital equipment and real estate;
- faster startup and shutdown capabilities because of low thermal inertia;
- a high degree of equipment modularity in all processing stages;
- very rapid feedback control capabilities;
- a high degree of product monitorability;
- high predicted equipment reliability; and
- reduced maintenance costs, resulting in improvements in reliability, modularity, control, and speed of startup or shutdown.

. Plasma treatment is used to control the fiber surface chemistry and surface energy to control the level of chemical affinity at the interface between the fiber and resin.

11A. Principal applications

Carbon fibers are commonly used as the load-bearing components in composite aerospace and aircraft structures. More recently, large-tow carbon fibers have been applied broadly in consumer products, such as tennis racquets, fishing poles, and golf clubs. They are also finding limited use in the rehabilitation of civil infrastructure (e.g., bridge repair). Carbon fiber composites could provide a strong, lightweight substitute for common structural materials such as metal, wood, and fiberglass. However, high cost continues to prohibit widespread use carbon fiber in consumer products.

The recent breakthrough by ORNL in developing and demonstrating MAP Carbon Fiber Manufacturing offers a new technological approach to meeting the demand for carbon fiber by consumer industries, particularly the automotive industry. (See Fig. 1.) The domestic automotive manufacturers' interest in developing carbon-fiber-based composites for use in primary structural applications has increased significantly as the industry struggles to make lighter, more fuel-efficient, and safer vehicles. Currently, steel is the most commonly used structural material in vehicles. Carbon fibers offer significant weight-savings potential due to their high strength, high modulus, and low density. Typical carbon fiber reinforced polymers (CFRPs) have nearly half the modulus of elasticity, 50% greater strength, and nearly one-fifth the density of steel.



Fig. 1. The DaimlerChrysler Concept car makes extensive use of composites for weight savings.

MAP-processed fibers are comparable to commercial large-tow fibers in mechanical properties and other relevant properties. MAP production-line throughput may be increased by approximately fourfold over that of conventional carbon fiber processing. Speed increases, coupled with energy savings, operational flexibility, and lower equipment and land-use costs, combine to affirm that the manufacturing cost may be reduced substantially.

This invention is very significant in its potential market impact. The combination of MAP processing and ongoing efforts to develop new raw material forms that will lower raw material prices are likely to reduce carbon fiber prices below \$5.00/lb, widely believed to be the “magic figure” at which carbon fiber will begin to attain widespread commercial acceptance. The carbon fiber industry is presently a half-billion dollar industry worldwide; prices below \$5.00/lb can easily stimulate tenfold or greater growth over the next two decades.

Well over \$15M a year is currently being spent on joint government-industry research and development expressly targeting implementation of widespread use of CFRPs in the automotive industry to achieve strategic economic competitiveness and environmental protection goals. However, implementation would require a reliable source for large volumes of inexpensive fiber. An example frequently cited informally in the automotive composites industry is that a relatively simple conversion from steel to carbon fiber composite as the structural material for tie rods on a typical mid-size car would require

carbon fiber quantities outstripping current production capacity. Automotive original equipment manufacturers and their suppliers agree that many other candidate applications would also each require significantly larger quantities of low-cost carbon fiber than are currently available. This type of conversion is currently technically feasible but cannot be economically justified until material costs decrease significantly. Adoption of MAP processing technology has the potential of achieving approximately half of the cost savings necessary to justify the widespread commercial acceptance of carbon fiber.

11B. Other applications

A wide variety of uses will be found for inexpensive, commercial-grade carbon and graphite fibers, particularly as load-bearing matrices in composites, which could be used, for example, instead of heavier (but currently cheaper) metal or resin-impregnated fiberglass parts. The following is a partial list of possible applications:

- **Transportation**

- **Aerospace and Aircraft.** Traditionally the market driver for premium carbon fibers for high-performance CFRP structures, these industries could also make use of inexpensive, commercial-grade carbon fiber in many less-demanding applications.
- **Ships and Pleasure Craft.** Low-cost carbon fiber will increase the affordability of topside CFRP structures, such as masts and antenna structures, and could be used to strengthen and lighten keels, hulls, decks, and bulkheads.
- **Rail Cars.** Lighter rail cars can enable higher top-end speeds or lower energy demands in high-speed rail applications while respecting axle-load limits. Material cost is presently a major barrier to rail-car applications.
- **Cargo Containers.** Decreasing container weight and cost while maintaining equivalent structural capacity would increase freight capacity and therefore, revenue. In addition, CFRPs may find application in blast-hardened, modular luggage containers for commercial aircraft.

- **Infrastructure**

- **Structures.** CFRPs are ideal materials from which to fabricate strong, lightweight, modular, corrosion-proof structures.
- **Bridges.** Carbon fiber is increasingly being used as a material for repairing bridges. In new construction, CFRPs would enable faster, modular bridge construction; increased live load capacity; increased durability; and reduced rigging requirements.

- **Signs.** CFRPs are structurally attractive for sign poles and frames, because of their durability, higher specific impact resistance, corrosion resistance, and improved vibration characteristics.
- **Utility Poles.** Wood utility poles weather rapidly and break too often. Carbon fiber composite utility poles would be superior in both respects but are much too expensive at present material prices.
- **Marine Structures.** Pilings, piers, and fenders would not be subject to wood borers, corrosion, and other life-limiting factors and would be much simpler and less expensive to install than those made of wood and metal.
- **Energy Production**
 - **Offshore Platforms.** Because of weight limitations on deepwater offshore oil platforms, the use of CFRPs on them is economical, even at current prices; further price reductions would increase their use and would help to increase U.S. oil production.
 - **Pipe and Tubing.** Price reductions will increase the use of lightweight pipe and tubing in offshore applications (especially piping that must be deployed from ships) and may change the economics of onshore applications such as distribution pipelines.
 - **Oil Wells.** Much of the equipment used for drilling, completion, and stimulation of oil wells benefits from the higher specific strength or modulus of CFRPs. Some applications are economical at present material costs; many others will become economical as costs decrease.
 - **Windmills.** CFRP wind turbine blades can be considerably longer than those made of glass-reinforced composites, wood, or other materials. Because of the cost, few blades are presently made from CFRPs.
- **Sporting Goods.** Mature applications, such as tennis racquets, golf club shafts, fishing poles, skis, and ski poles will benefit from further material cost reductions. Development of emerging applications such as bicycles, snowboards, canoes and kayaks, and camping equipment would require cost reductions.
- **Hardware.** Carbon fiber, principally commercial grade, is used in a number of mechanical hardware applications, such as tubes, shafts, and pressure vessels.
- **Electrical and Electronic Equipment.** Carbon composites are useful for reducing weight and providing shielding against electromagnetic interference in electronics applications, notably in cell phones and laptop computers. This is already a significant and rapidly growing market; reduced material cost will serve to further accelerate its growth.

- **Musical instruments.** Carbon composites, because of their vibrational characteristics, can richly affect tone in stringed musical instruments, and are becoming popular materials in high-end guitars. Material cost reductions will accelerate growth in this market.
- **Medical applications.** Some X-ray tables are now constructed from carbon fiber because its lower X-ray-attenuation characteristics enable sharper X-ray images. The high specific strength and modulus are attractive for high-precision robotics applications, such as those used in certain cancer therapy equipment.

12. Summary

Microwave-Assisted Plasma (MAP) Carbon Fiber Manufacturing is a revolutionary technology for carbonizing and graphitizing carbon fibers at much higher speeds and significantly lower costs than those achievable by present industrial practice. A rigorous cost analysis has estimated that this technology can reduce carbon fiber costs by almost 20%. Additional benefits include the ability to tailor the fiber surface condition to achieve enhanced chemical bonding to the resin as well as mechanical bonding (interlocking).

MAP processing reduces cost very early in the CFRP value stream, thus reducing markup and tremendously reducing final product cost. MAP processing allows the carbon-fiber production line to become a module in an integrated production factory in which the starting product is raw material (e.g., a precursor or resins) and the end product is the final assembly (e.g., an automobile chassis component). MAP processing features that are critical to integration in a “super factory” include compactness, high throughput, low energy demand, high reliability, modularity, excellent monitorability and control, and low maintenance requirements.

MAP processing will be a key element in making CFRPs affordable for automotive manufacturing and other industrial applications. When CFRPs have been proven to be an acceptable material for automotive manufacturing, from both technical and cost perspectives, they will rapidly be adopted by other industrial segments and will become pervasive materials. We estimate that these events will result in a tenfold or greater increase in the demand for carbon fiber over the next two decades.

We are poised on the brink of another materials revolution—we are entering the “carbon era.” MAP carbon fiber manufacturing will become a critical technology in this materials revolution.

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Attachments

A. Confirmation Letters

B. Pictures

1. Figure 2
2. Figure 3
3. Figure 4
4. Figure 5
5. Figure 6
6. Figure 7

C. Carbon Fiber Analysis

1. Electrical Properties
2. Mechanical Properties
3. Tensile Strength Properties
4. Morphological Properties

D. Publications

Attachment A

Confirmation Letters

Attachment B

Illustrations of the Microwave-Assisted Plasma Carbon Fiber Manufacturing Process



Figure B.1. ORNL researchers Felix Paulauskas (left), Terry White (center), and Ken Yarborough (right) monitor the output temperature of carbon fiber produced by the ORNL Microwave-Assisted Plasma (MAP) Carbon Fiber Manufacturing Process.

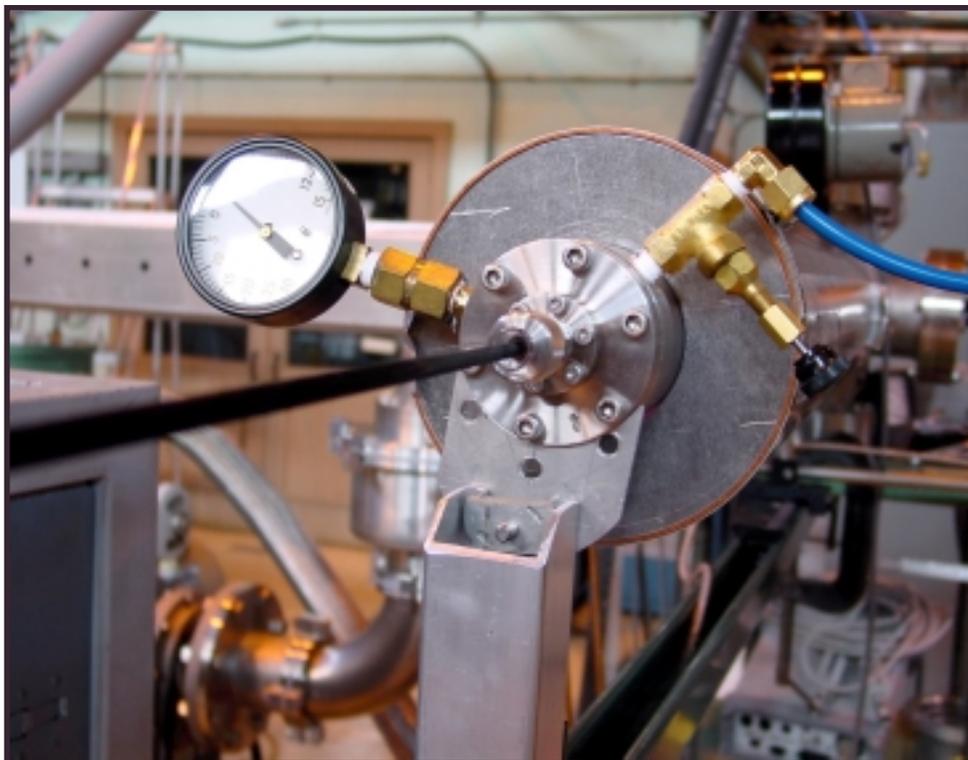


Figure B.2. View at input end of the MAP manufacturing process showing the carbon fiber tow input.

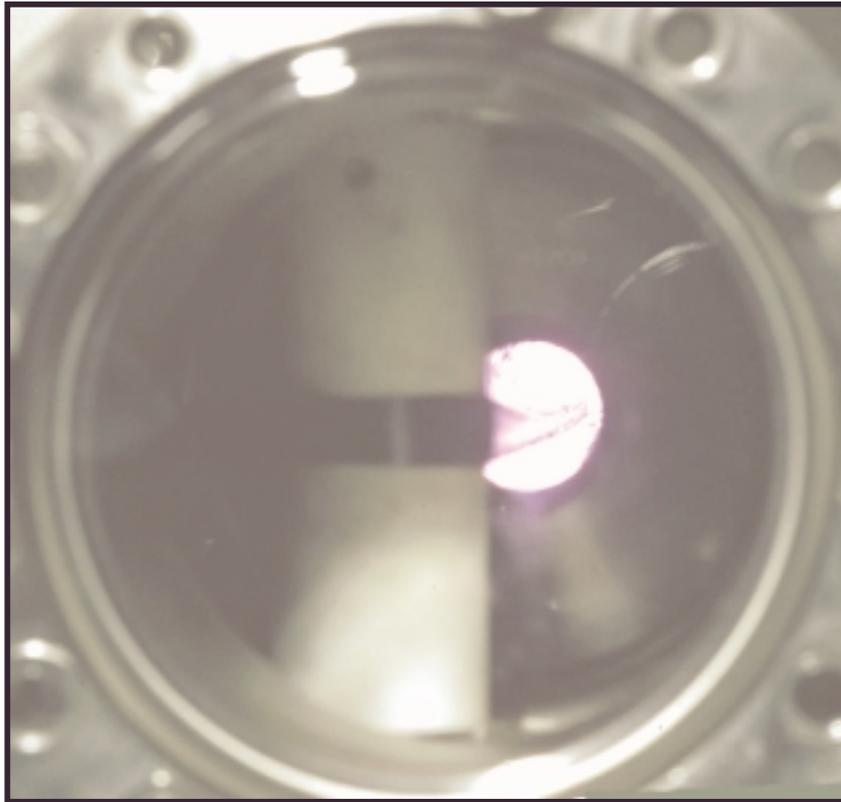


Figure B.3. The fully oxidized carbon fiber tow is flattened with a ceramic roller as it enters the microwave plasma discharge.



Figure B.4. Terry White, Ken Yarborough, and Felix Paulauskas (left to right) measure the linear electrical resistance of the MAP carbon fiber.



Figure B.5. The MAP carbon fiber manufacturing line.



Figure B.6. View at output end of the MAP carbon fiber manufacturing process showing the take-up winder.

Attachment C

Carbon Fiber Analysis

The following are comparisons between conventionally manufactured carbon fiber and carbon fiber manufactured by the ORNL Microwave-Assisted Plasma (MAP) process. The MAP process was characterized at low line speed (7.5 in/min) and high line speed (20.5 in/min). Both conventional and MAP processes were evaluated for 50K tows.

C.1. Electrical Properties

	Conventional F3(C)	MAP (low speed)	MAP (high speed)
Linear Electrical Resistance($\times 10^{-2}$ ohm/cm)	7.80	8.37	9.80
Electrical Resistivity* ($\times 10^{-3}$ ohm-cm)	1.67	1.57	1.89
* Electrical resistivity is a measure of the ease at which a material transmits electricity and is independent of material geometry.			

C.2. Mechanical Properties

	Conventional F3(C) 50K Tow	MAP (low speed)	MAP (high speed)
Density** (gm/cm ³)	1.77	1.83	1.82
Calculated Tow Area ($\times 10^{-2}$ cm ²)	2.17	1.90	2.03
Filament Diameter ⁺ (μ m)	7.43	6.97	7.19
** Density is a basic indicator of the processing condition during manufacturing and general indicator about carbon fiber transformation during processing.			
⁺ Diameter is based on a tow consisting of 50,000 filaments.			

C.3. Tensile Strength Properties

A carbon fiber will be judged and selected for an application on these properties. These are the final criteria related to the processing condition of the carbon fiber.

	Conventional F3(C)	MAP (low speed)	MAP (high speed)	PNGV Program Goals
Modulus ($\times 10^6$ lb/in. ²)	31.1	31.7	30.5	25
Ultimate Strength ($\times 10^3$ lb/in. ²)	485.3	424.1	384	300
Elongation at break (%)	1.5	1.3	1.22	1.0

The strength properties of the carbon fiber depend upon the carbon fiber processing, surface treatment, sizing, and mechanical specimen manufacturing. The carbon fiber surface treatment, sizing, and tensile test specimens were prepared under identical conditions, to exclude any possible induced differences between the conventional and MAP carbon fibers.

C.4. Morphological Properties

Wide-angle x-ray diffraction evaluations were undertaken to gain insight of basic structural morphological characteristics of carbon fiber processed by different technologies. Results of this evaluation will allow a qualitative comparison between carbon fibers with different structural characteristics. Any possible effect of precursor chemistry and purity are eliminated because the MAP fiber and the conventional F3(C) from Fortafil were fabricated from identical PAN-precursor. A diffractogram measures the scattering of an incident x-ray beam on the crystalline structure of a material. The scattering peak and valleys are a function of the crystalline structure of the material. The geometry of the crystal structure and their orientation in the material will determine the magnitude and location of the peaks in the diffractogram. As applied to carbon fiber, x-ray diffractometry will produce two peaks. The first peak at approximately 16 degrees (2-theta) represents non-converted oriented polymeric material. The second peak at approximately 26 degrees (2-theta) represents polymeric material converted to carbon and/or graphite. Fig. 1 shows the x-ray diffractogram of an early processing stage (fully-oxidized/stabilized PAN precursor) of PAN-based carbon fiber. No one peak is dominant which indicates that the material has undergone incomplete processing. Fig. 2 shows the x-ray diffractogram of the low-cost commercial carbon fiber product (F3(C)/Fortafil). A single peak near 26 degrees shows that the carbon fiber has been processed to the point where most of the material has been converted to carbon or graphite. Fig. 3 depicts the x-ray diffractogram of the MAP carbon fiber product representative of the tested samples described in this report and is similar to the diffractogram of conventional carbon fiber shown in Fig 2. Both Figs. 2 and 3 indicate a high level of material conversion toward carbon/graphite. Fig 4 is a comparison of the x-ray diffractograms for commercial (F3(C)/Fortafil) and MAP carbon fiber produced under different microwave energy processing levels. All Fig. 4 diffractograms show the same general profile, but the predominant peaks vary in amplitude with the highest peak (curve b) representing the highest energy process sample and curve c representing the lowest. Curve. b shows a higher level of conversion or processing of polymer to carbon/graphite. Carbon fiber product represented by the curves. b and c were produced continuously over a period of only a few tens of seconds by changing the microwave power levels. This clearly shows that the MAP manufacturing process can produce a variety of different qualities of carbon fiber very rapidly with little down time. The conventional carbon fiber product is clearly in between the two MAP products. The MAP process can tailor the properties of the carbon fiber very rapidly. This is in sharp contrast to conventional oven processing of carbon fiber, which requires many hours to allow the large processing ovens to come to thermal equilibrium. The MAP manufacturing process can change the temperature of the carbon fiber rapidly because the thermal mass of the MAP system is much less than comparable conventional carbon fiber processing systems. We observe that all of the carbon fiber processing (from fully oxidized PAN precursor to highly-graphitized, high-cost, high-quality carbon fiber typically used in aerospace application) occurs only in the plasma region over a length of approximately 1 meter, at a line speed of 52 cm/min! This translates to a residence time of only 30 seconds. If the length of the plasma is doubled then the same quality carbon fiber can be produced at double the line speed. If the line speed is doubled for the 1 meter length plasma case, then carbon fiber can still be produced, but at slightly lower strength. However, this high speed MAP product still surpasses the PNGV program goals, and is quite acceptable for automotive applications.

In conclusion, we can state firmly that in all tests the MAP manufactured carbon fiber is equal to or better than the corresponding low-cost conventionally produced carbon fiber.

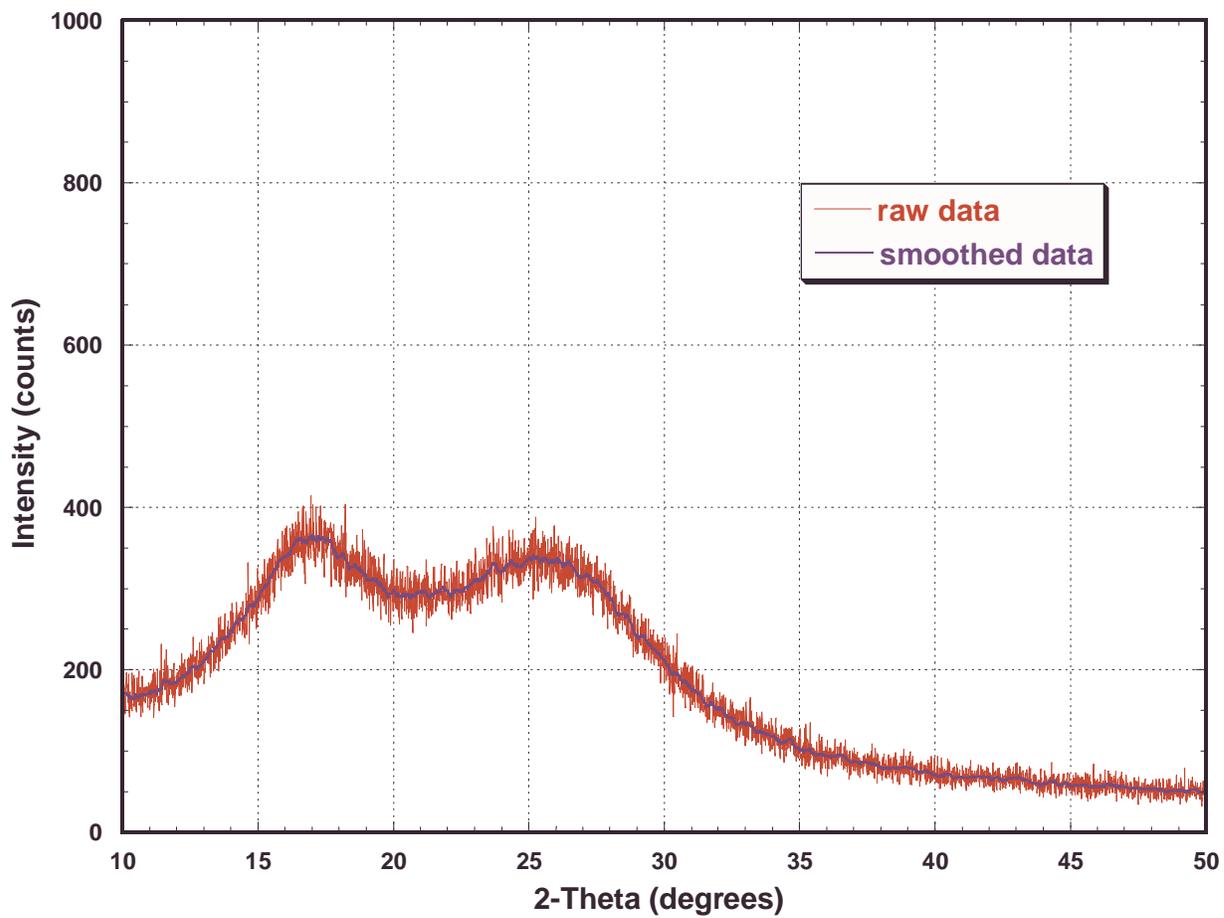


Figure 1. The x-ray diffractogram for fully-oxidized/stabilized PAN precursor used for both conventional and MAP processes.

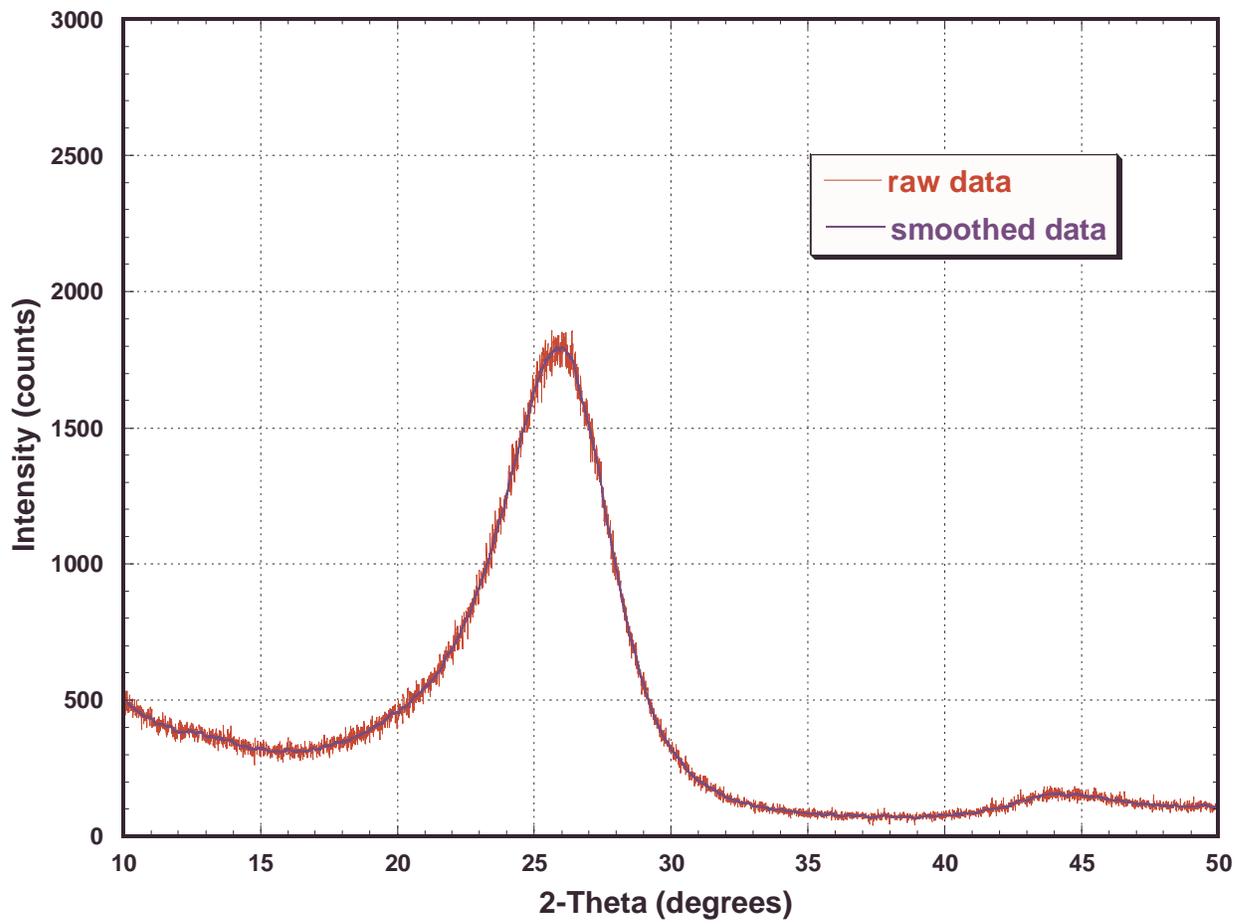


Figure 2. The x-ray diffractogram for low-cost commercial carbon fiber product F3(C)/Fortafil.

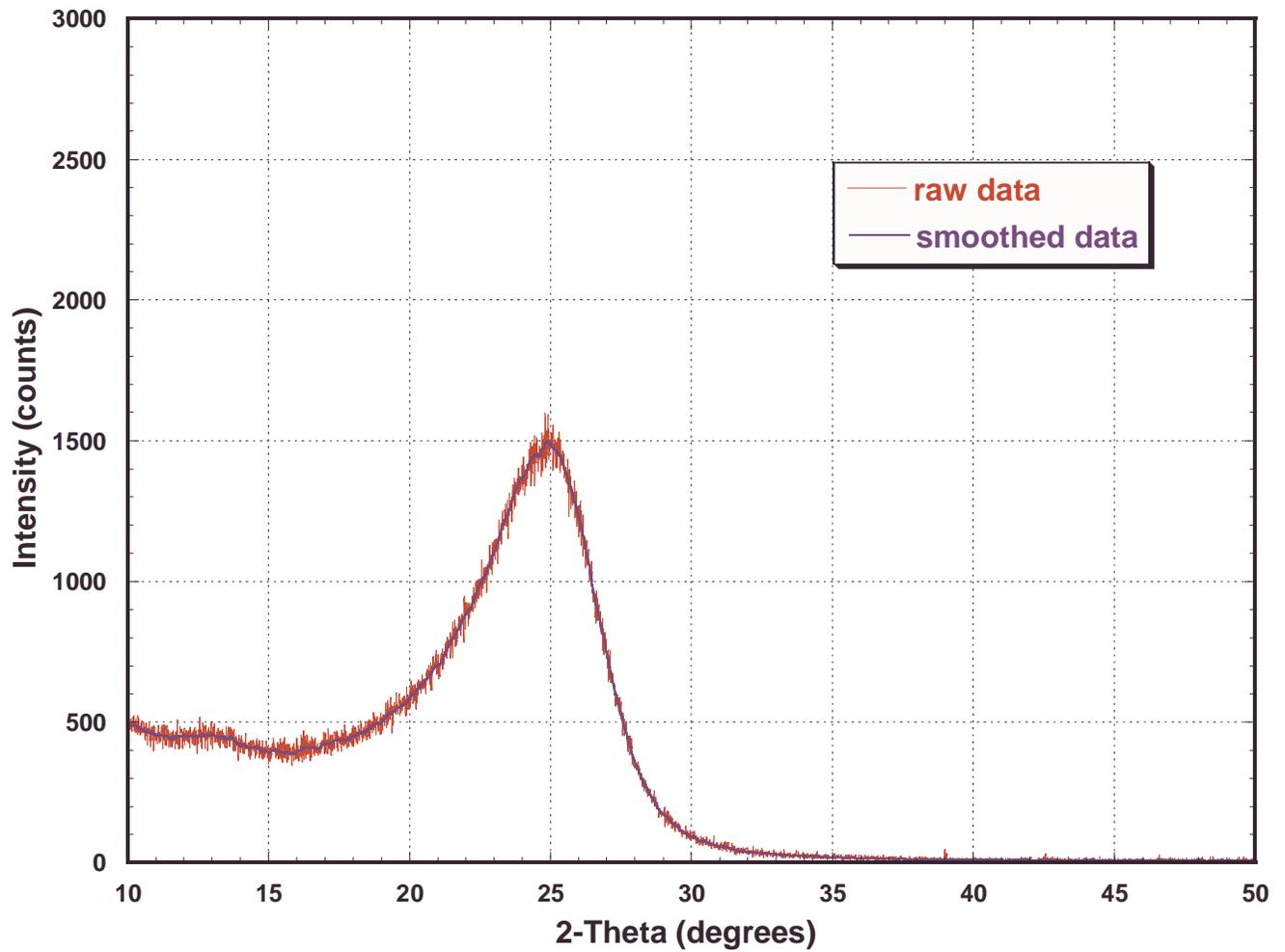


Figure 3. The x-ray diffractogram for the MAP carbon fiber product and is representative of the tested samples described in this nomination.

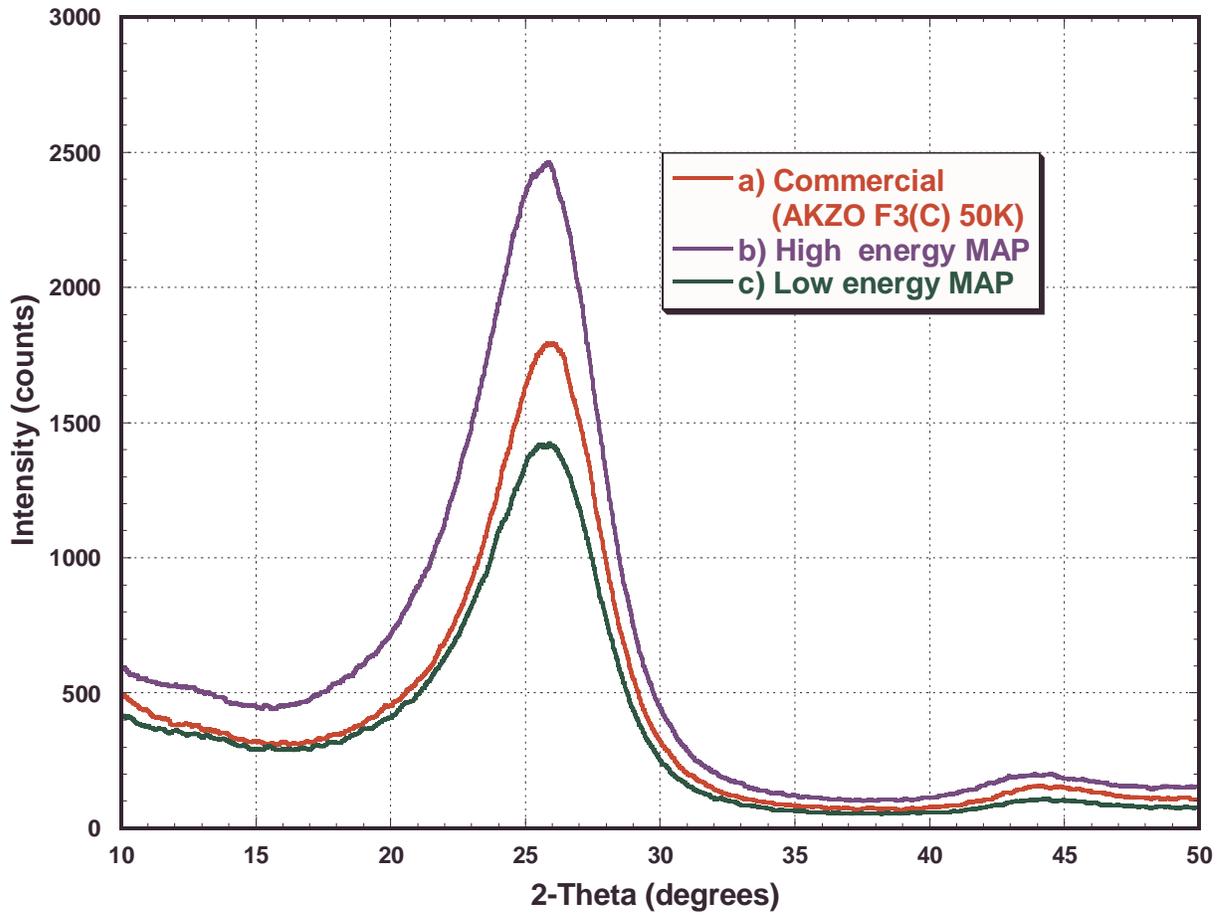


Figure 4. Comparison of the x-ray diffractograms for commercial and MAP carbon fiber produced under different microwave energy processing levels.

Attachment D

Publications