Autocomposites Workshop

Kickstarting the widespread adoption of automotive carbon fiber composites

7,8,9 November 2012
Troy, MI

Rocky Mountain Institute®

Autocomposites Project Overview & FAQ

Automotive Carbon Fiber Industry Context

Challenges to Widespread Implementation

Manufacturing Innovation

Design & Analysis Enhancement

Lifecycle Considerations

Approach to Overcome Challenges

Overview

Lightweight Autocomposites

Summary

RMI is committed to reducing U.S. oil dependence and enhancing the competitive positioning of the U.S. automotive sector by catalyzing a shift to ultralight, ultrastrong autobodies made of advanced materials, particularly carbon fiber composites. Light autobodies dramatically improve fuel efficiency and allow powertrains to be smaller, lighter, more efficient, and more cost-effectively electrified. Understanding the barriers, developing consensus on the way forward, and spurring a transition through collaborative risk sharing, policy, and government support of research and development will be critical to success.

The Prize

Strong U.S. design and manufacturing know-how, reduced oil dependence, CAFE compliance, jobs, global competitiveness, security and environmental stewardship.

A Collaborative Approach

Barriers hampering the widespread adoption of automotive composites in the U.S. can be explored, understood, and addressed in a collaborative and coordinated way to dramatically increase the adoption of this material.

(1) Develop Consensus View

RMI has engaged stakeholders to identify the technical, institutional, and economic barriers to widespread adoption of automotive composites.

(2) Convene Key Players in a Workshop

RMI will convene automakers, suppliers, technology providers, toolmakers, academia, and government in a workshop on November 7,8, & 9 in Troy, MI to address the main barriers to implementation.

(3) Workshop Outcomes

RMI will help develop, with key stakeholders, the actions needed to catalyze a U.S.-based transformation to automotive carbon fiber composites, e.g. via consortium and joint venture formation, purchase agreements, knowledge sharing, targeted government action, and a transitional pathway to scale adoption that moves from an initial part-by-part substitution approach to full implementation.

This is Just the Beginning...

This year's workshop will identify initial pathways—at the individual part level—to widespread adoption of automotive composites. In order to achieve a truly transformative shift to ultralight autobodies, these initial pathways will need to be monitored, multiplied, expanded, and scaled. RMI plans to both ensure implementation of this year's workshop results and expand our efforts to the whole-vehicle level to achieve breakthrough efficiency gains and ultimately enable an electrified, fossil-fuel-free vehicle paradigm.

Hypothesis

The following themes, if addressed collaboratively, will help unlock the barriers to automotive carbon fiber composites:

Manufacturing Innovation:

Achieving cost-effective manufacturing will require that key challenges be addressed:

-Reducing Material Cost
-Enhancing Part Manufacturing

Design & Analysis Enhancement:

A composites-based design regime will require an expansion of automotive engineering knowledge and toolsets:

-Designing for performance & producibility
-Enhancing design & analysis tools
-Designing for replacability & repairability

Life Cycle Considerations:

To viably replace current structural materials such as steel, composites will have to provide a viable lifecycle value proposition.

-Recylability
-Repairability

Approach: A Path to Scale

Adopting these design and manufacturing innovations and enhancements will require that key transitional challenges be addressed:

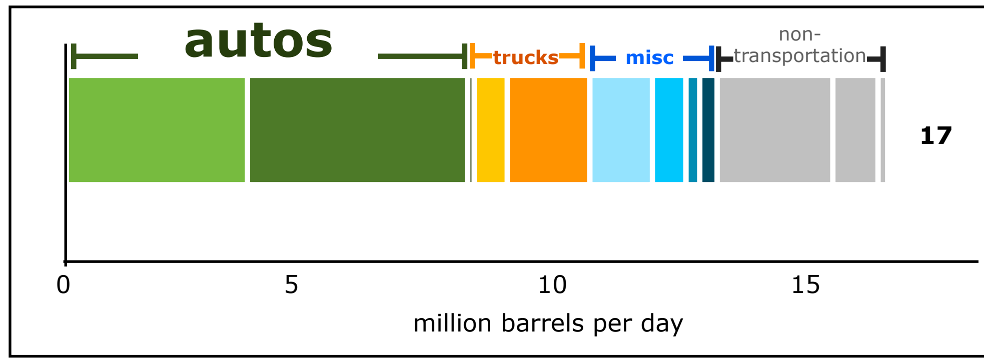
-Investment risk and capital availability
-Supply chain coordination
-Implementation pathway

About RMI

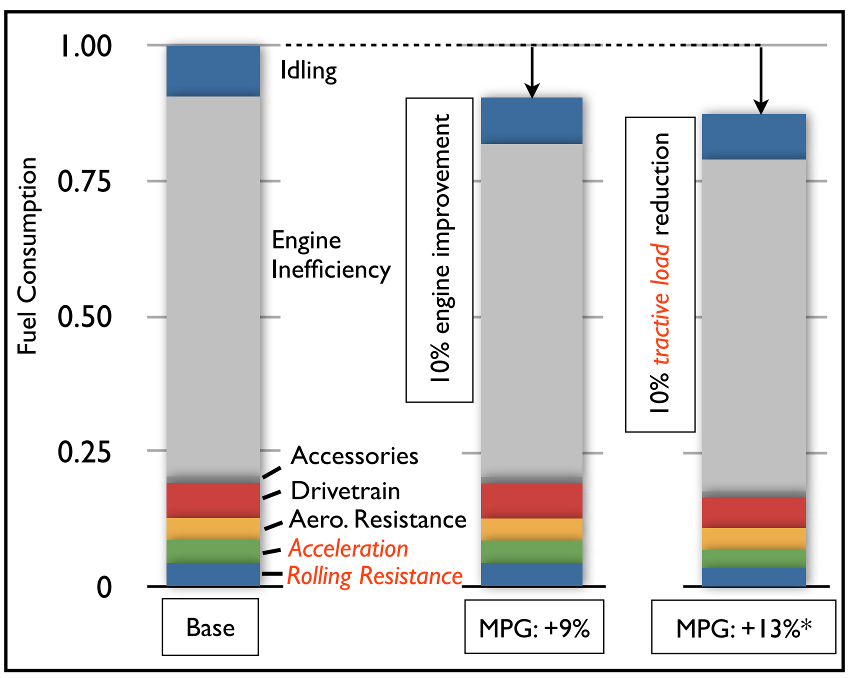
RMI is an entrepreneurial, nonprofit think-and-do tank that drives the efficient and restorative use of resources. Since 1991 RMI has been pursuing lightweighting in U.S. transportation, with particular focus on efficient auto design using advanced materials. Our recent book, *Reinventing Fire*, provides a comprehensive roadmap to get the U.S. off coal and oil by 2050.

Why focus on passenger vehicles?

U.S. autos burn more than 8 million barrels of oil per day: 49% of all domestic consumption. Improving vehicle efficiency is a cornerstone of reducing U.S. oil dependence.



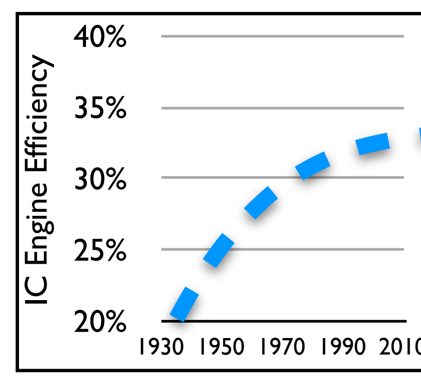
Why weight reduction vs. improved powertrains?



A lightweight architecture reduces "tractive load"—the energy required to propel the vehicle—by reducing tire losses from rolling resistance and allowing a smaller, lighter powertrain to deliver the same performance with less fuel.

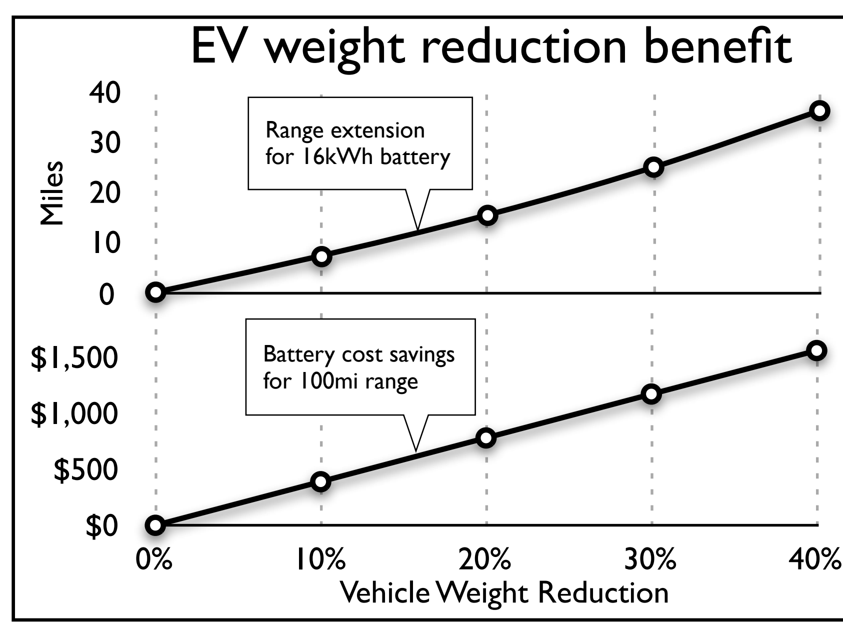
These benefits extend to any powertrain technology.

While the great majority of research and development spending has gone to engines (as opposed to lightweight materials), engine efficiency has improved by only about 10% on average since 1975[1], and the next 10% will be much harder to get.

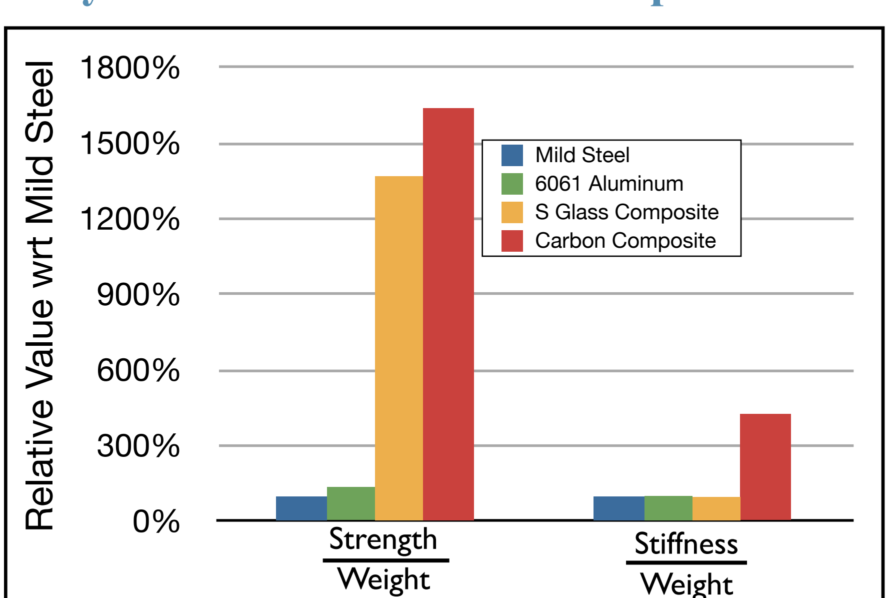


Electric vehicles (EVs) derive particularly compelling benefit from weight reduction, since a lighter architecture improves performance while extending range, or decreasing battery costs, or both.

BMW achieved a 20% weight saving (or 10% tractive load reduction) by implementing lightweight carbon fiber composite on their i3 EV. Much of the additional material cost was reportedly offset by battery savings.



Why focus on carbon fiber composite?



Carbon fiber composite is not applicable in all structural applications--the most likely scenario for a vehicle achieving substantial weight reduction is a mixed material solution in which metals and standard polymers continue to play important roles.

When it comes to strengh and stiffness per pound, however, carbon fiber composite offers unparalleled weight reduction potential.

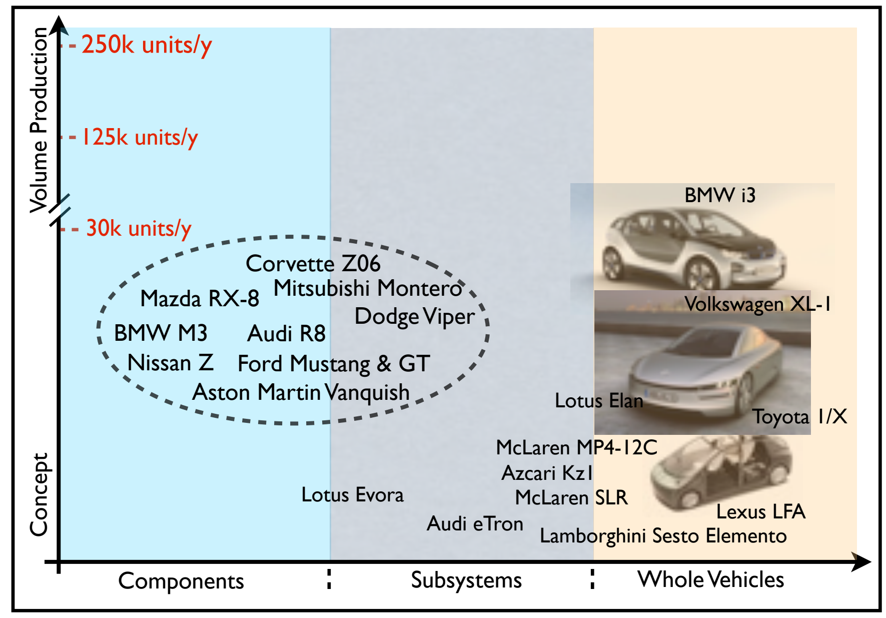
1. Historic engine efficiency trends based on engine data for 6 engine types, Myers & Foster, 2004
*Based on RMI model (EPA drive cycle). ANL indicates 16% improvement.

What's the current landscape?

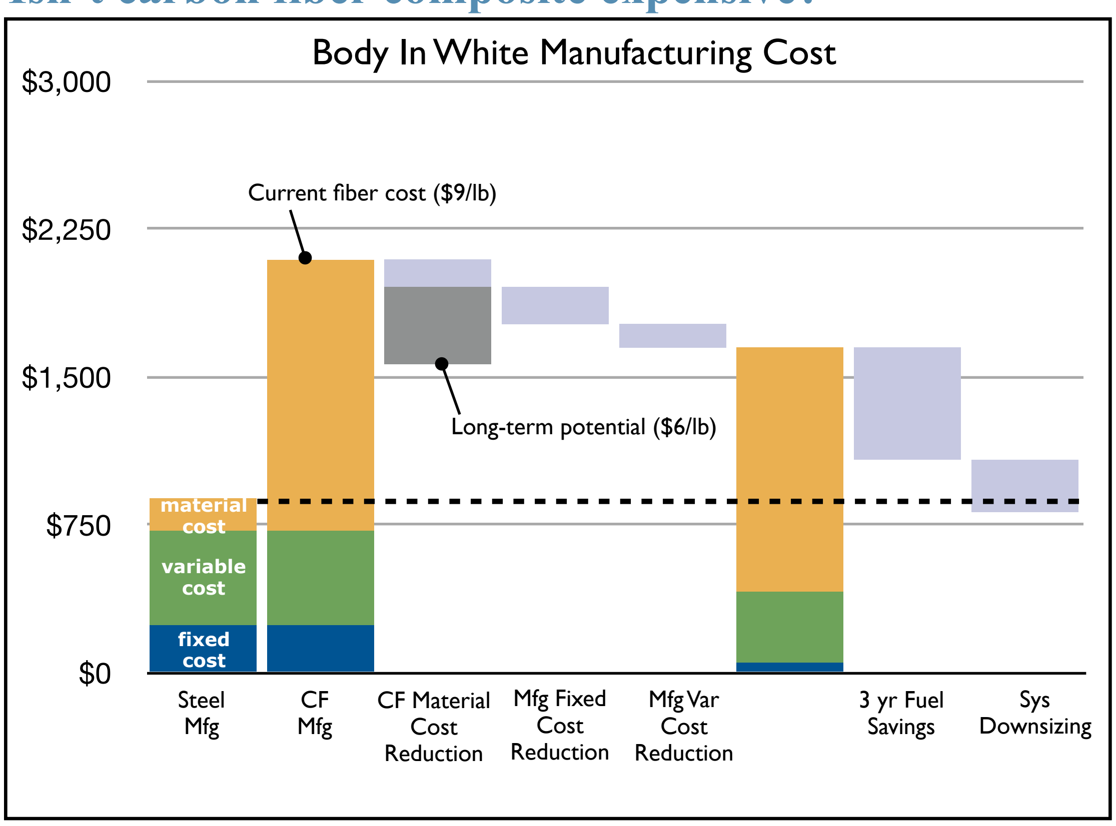
While German manufacturers appear poised to take the lead, U.S. automakers have begun introducing individual parts, mostly on high-end models, thereby building design expertise with composites while working out supply chain and tooling challenges on a small scale.

Existing consortiums include the Automotive Composites Consortium and the Oak Ridge Carbon Fiber Composites Consortium. Several partnerships have also formed between carbon fiber producers and U.S. automakers, such as GM-Teijin and Ford-Dow. DOE is committed to expanding the use of advanced materials, including carbon fiber composites, as part of its Vehicle Technologies Program.

Significant opportunity remains to more favorably position U.S. automakers and suppliers in a potentially transformed marketplace founded on lightweight autos.



Isn't carbon fiber composite expensive?

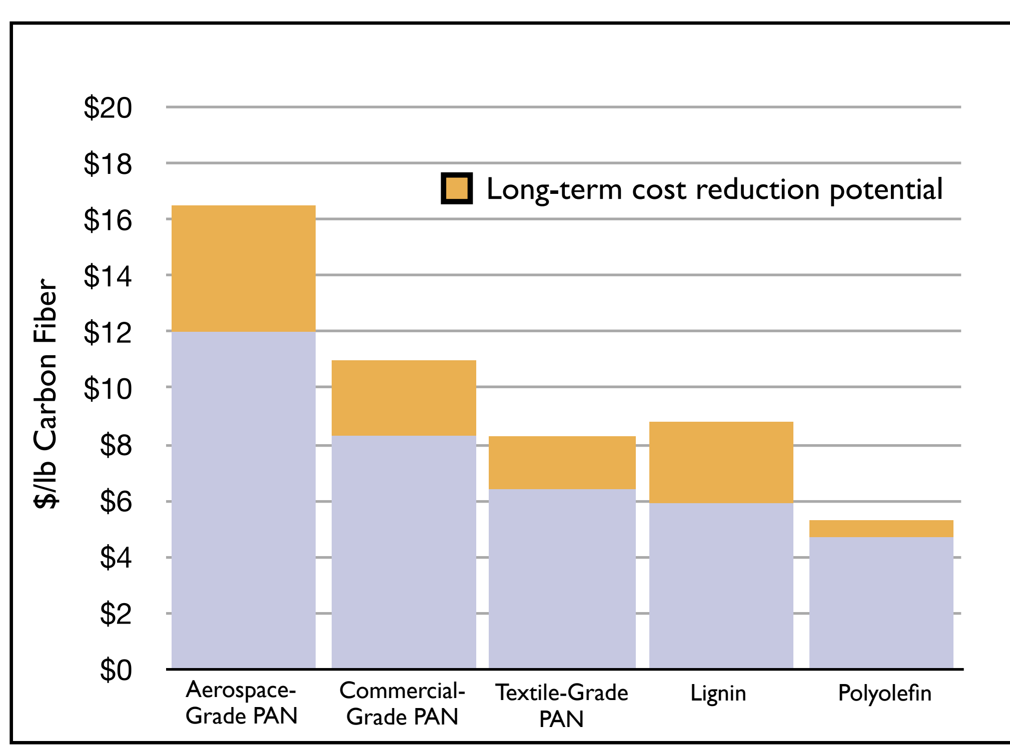


Material cost is currently much higher than for steel. That cost is potentially offset by manufacturing cost reductions, customer fuel savings, and powertrain downsizing, helping to make a carbon-fiber-composite-intensive lightweight vehicle a viable value proposition. However, manufacturing cost reductions are largely contingent on achieving sufficiently rapid manufacturing methods to enable scale production (50k vehicles per year or more).

Assumptions: $4/gal gas

What is it going to take to reduce carbon fiber raw material cost?

Raw material cost reduction levers include tailoring fiber grades to automotive use, economies of scale, advanced processing, and alternative precursors. Several technology pathways lead to a future carbon fiber raw material price of ~$6/lb (including resin).



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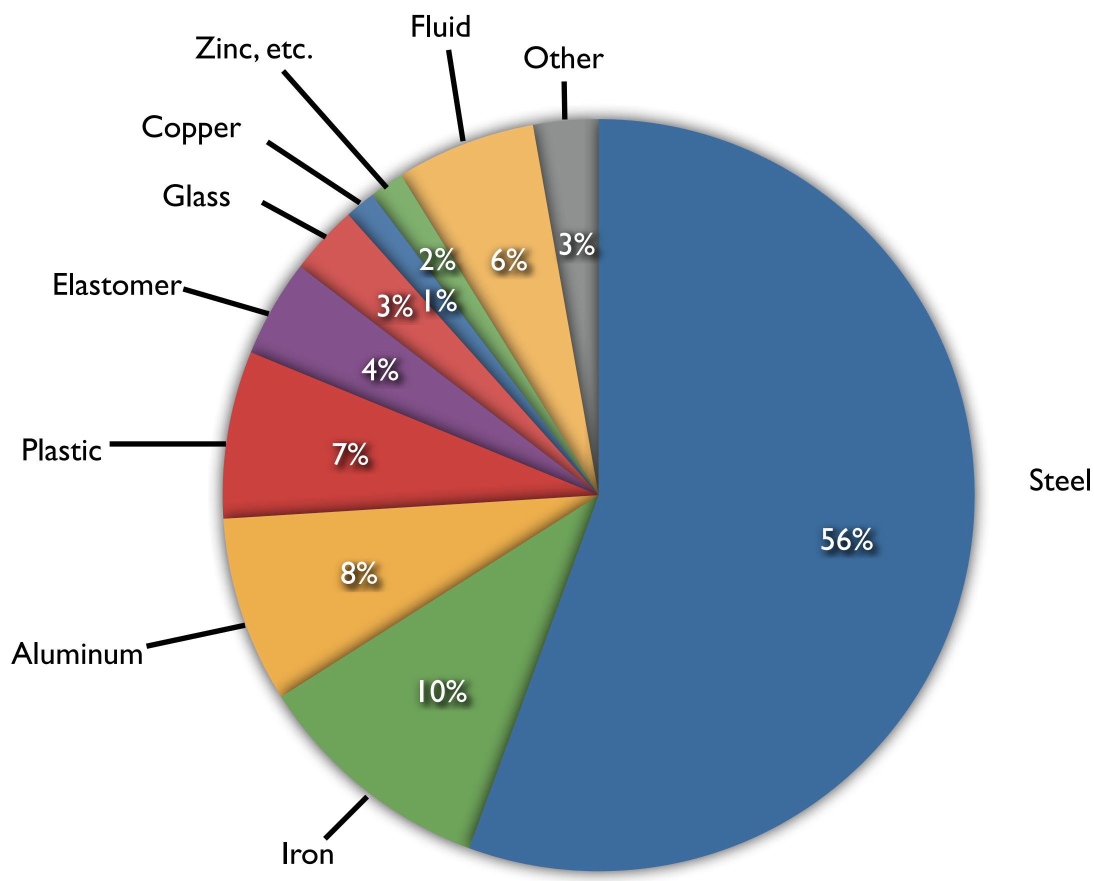
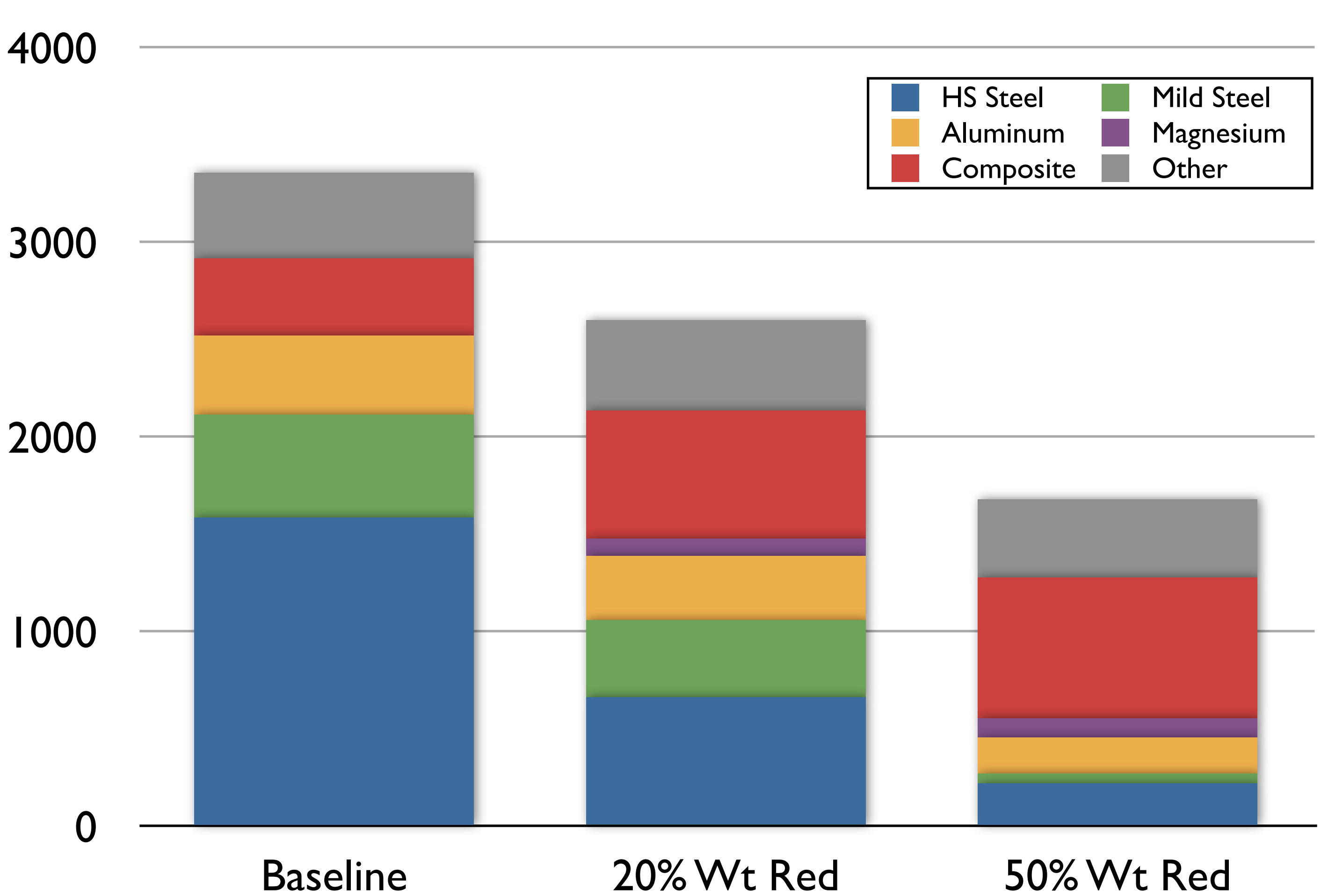
Passenger vehicles are composed of a diverse combination of materials.



Advanced vehicles are likely to be similarly materially diverse even as composites replace heavier metals.



Sources: McKinsey & Co; ORNL; Hypercar, Inc; Toyota

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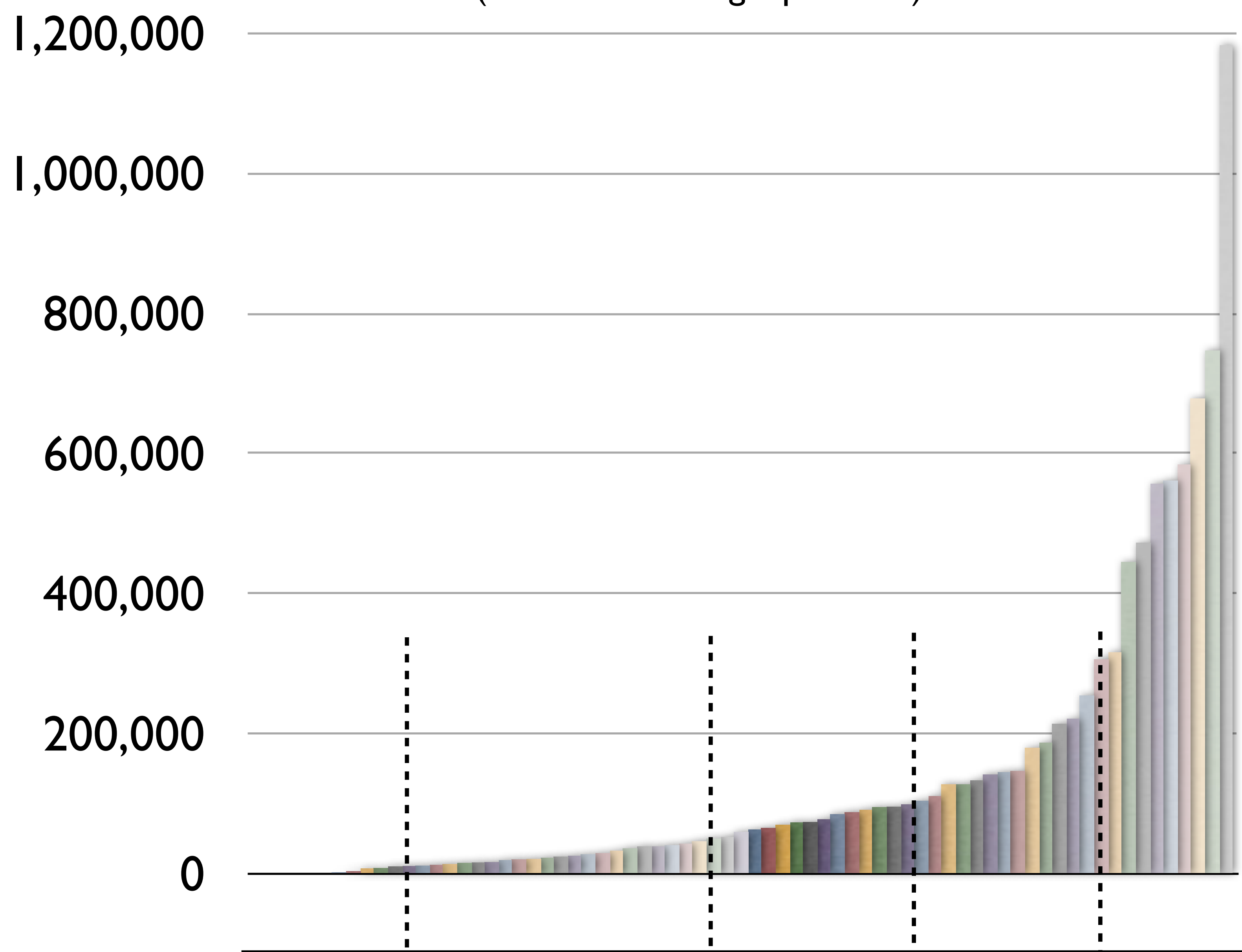
Context

Automotive Production Volume Summary U.S. Market - 2010

Platform Production Volume
(Each bar is a single platform)

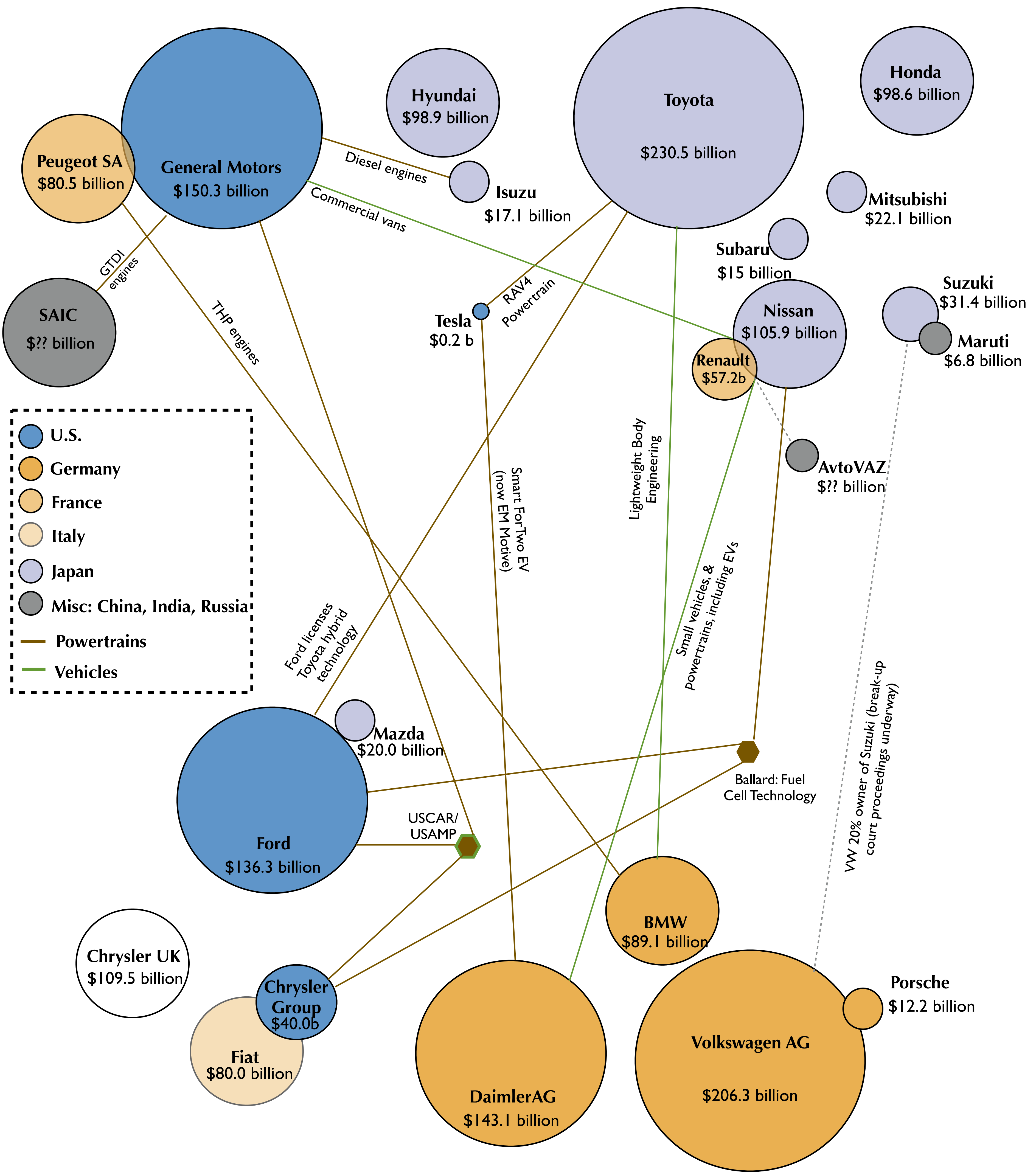


	<10k	10-50k	50-100k	100-250k	>250k
Models	12	36	34	46	40
Platforms	10	23	15	12	14
Total Volume	25k	566k	1.1M	2.1M	6.4M

Sources: WCM 2010, U.S. OEMs only (includes Fiat-Chrysler), does not include 6M vehicles for which platform data is unavailable

Context

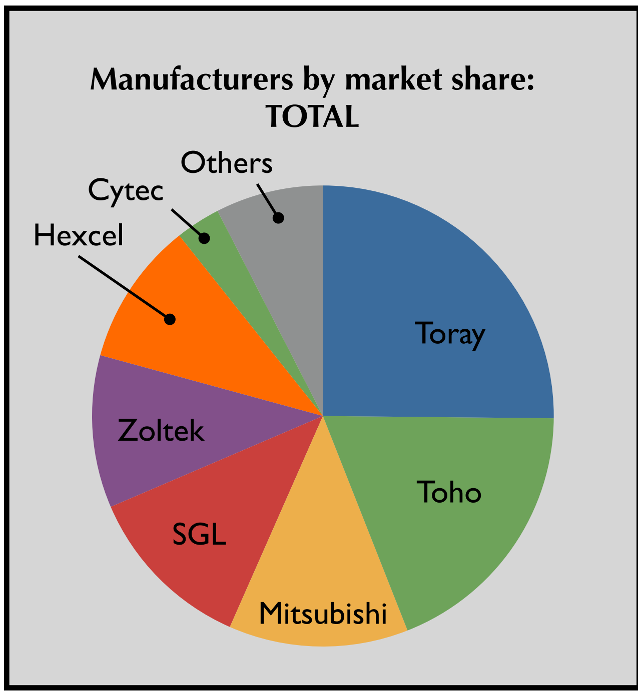
Collaboration and joint development are well-established in the auto industy

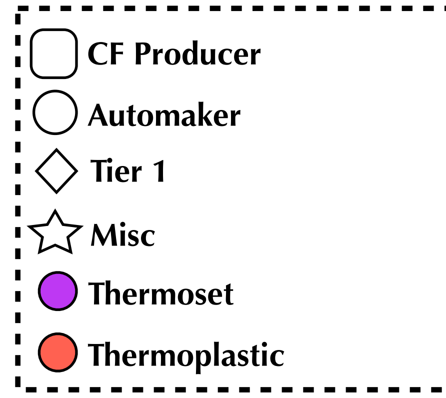


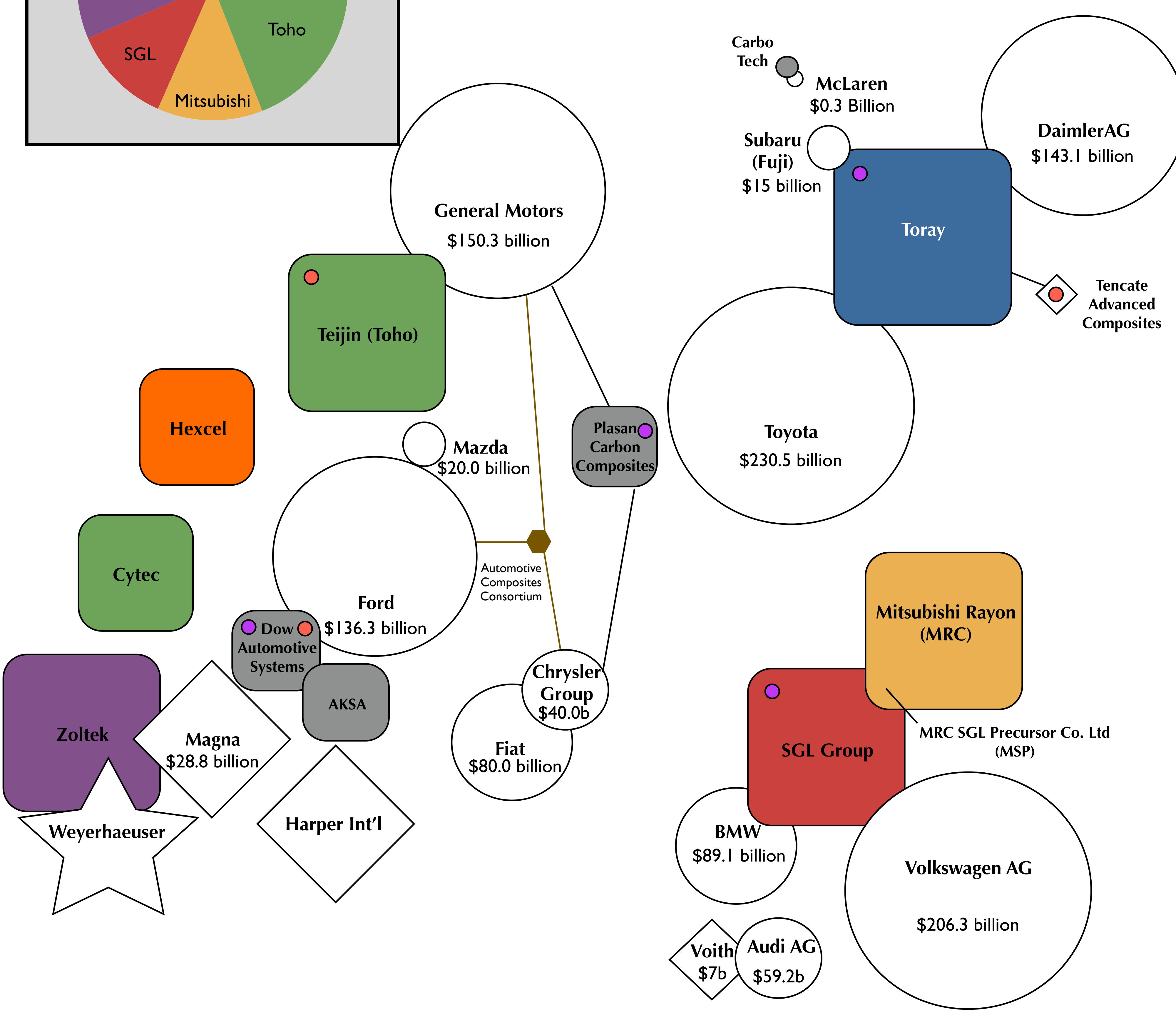
Sources: Adapted from David Pierce, Detroit Free Press, Hoover's

Context

Several partnerships have been established between OEMs, Tier 1s, & carbon fiber producers



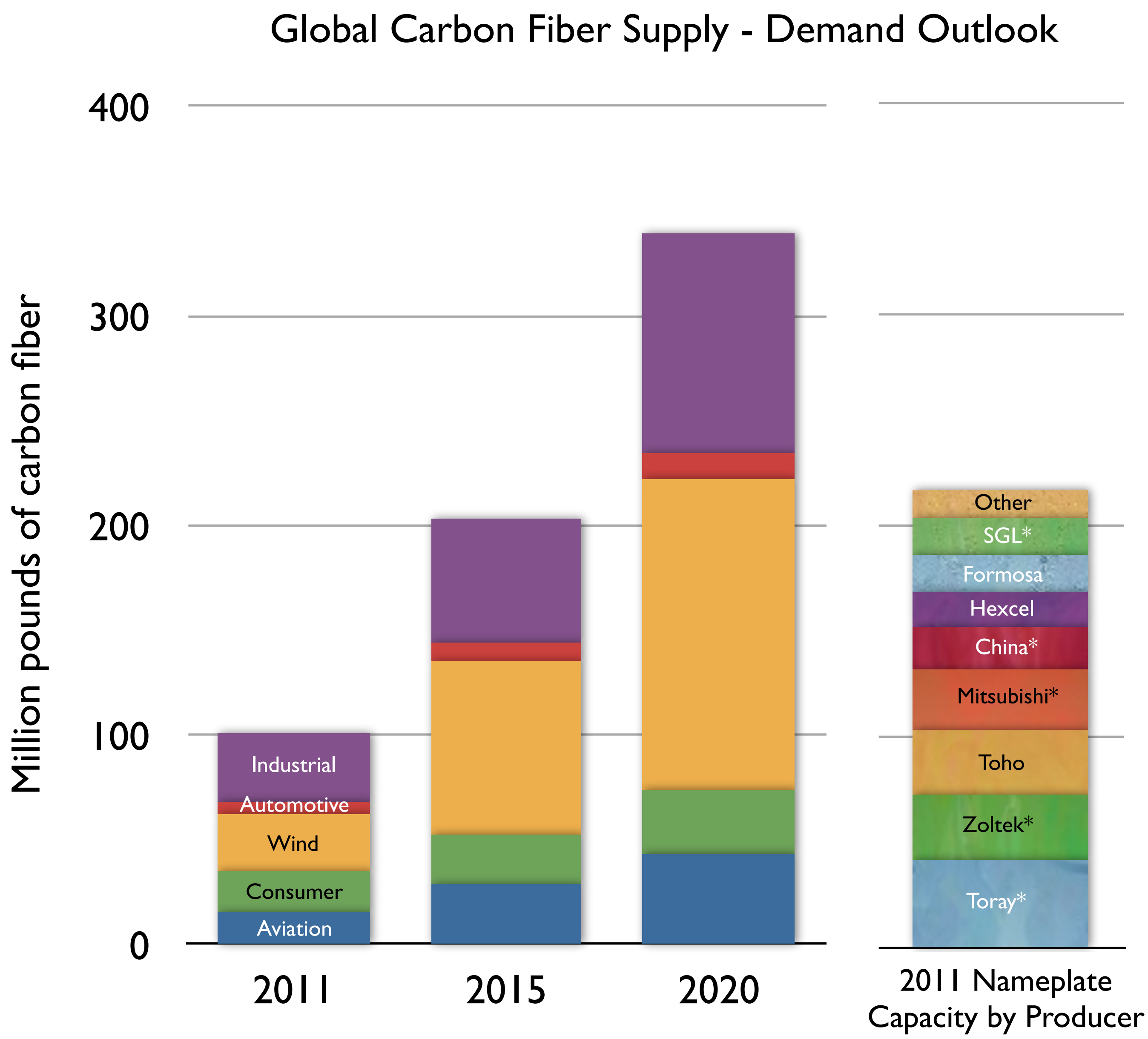




ORNL; David Pearce, Detroit Free Press; Hoover's; Weyerhauser; Zoltek

Context

Current capacity exceeds demand



If **20 lb** of carbon fiber were implemented...	global demand would increase by...
in a single mainstream vehicle model	5 million pounds (5%)
in every U.S. military humvee	3 million pounds (3%)
in the entire sports car market	2.5 million pounds (2.5%)

If a carbon fiber **body in white** were implemented...	global demand would increase by...
in a single sports car model	2 million pounds (2%)
in the entire U.S. sports car market	15 million pounds (15%)
in a single mainstream vehicle model	30 million pounds (30%)

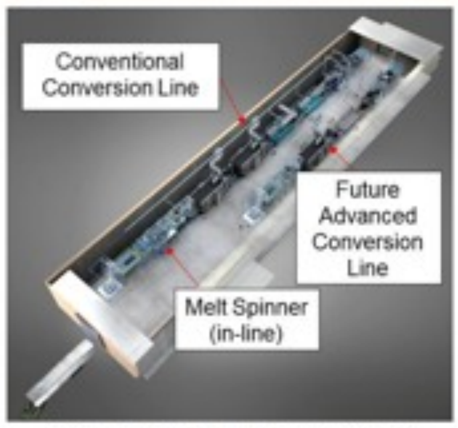
AJR consulting, Compositesworld, Automotiveworld
*Significant providers of industrial grade fiber (as opposed to aerospace grade). SGL and Zoltek specialize entirely in industrial grade and account for >40MM lb of annual production.

Context

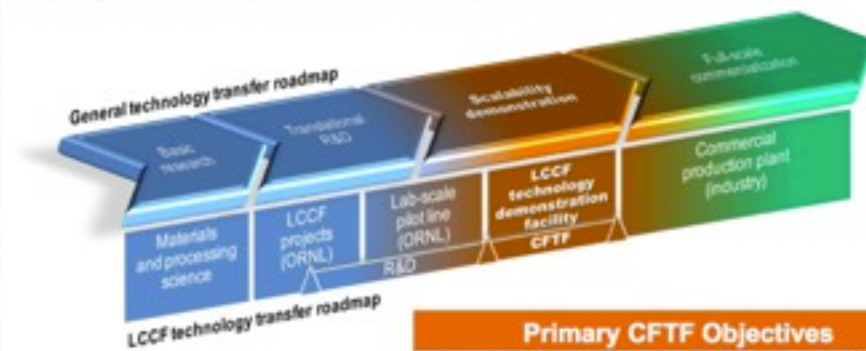
Oak Ridge's Carbon Fiber Technology Center can help bridge from R&D to scale production.

Carbon Fiber Technology Center (CFTF) Snapshot

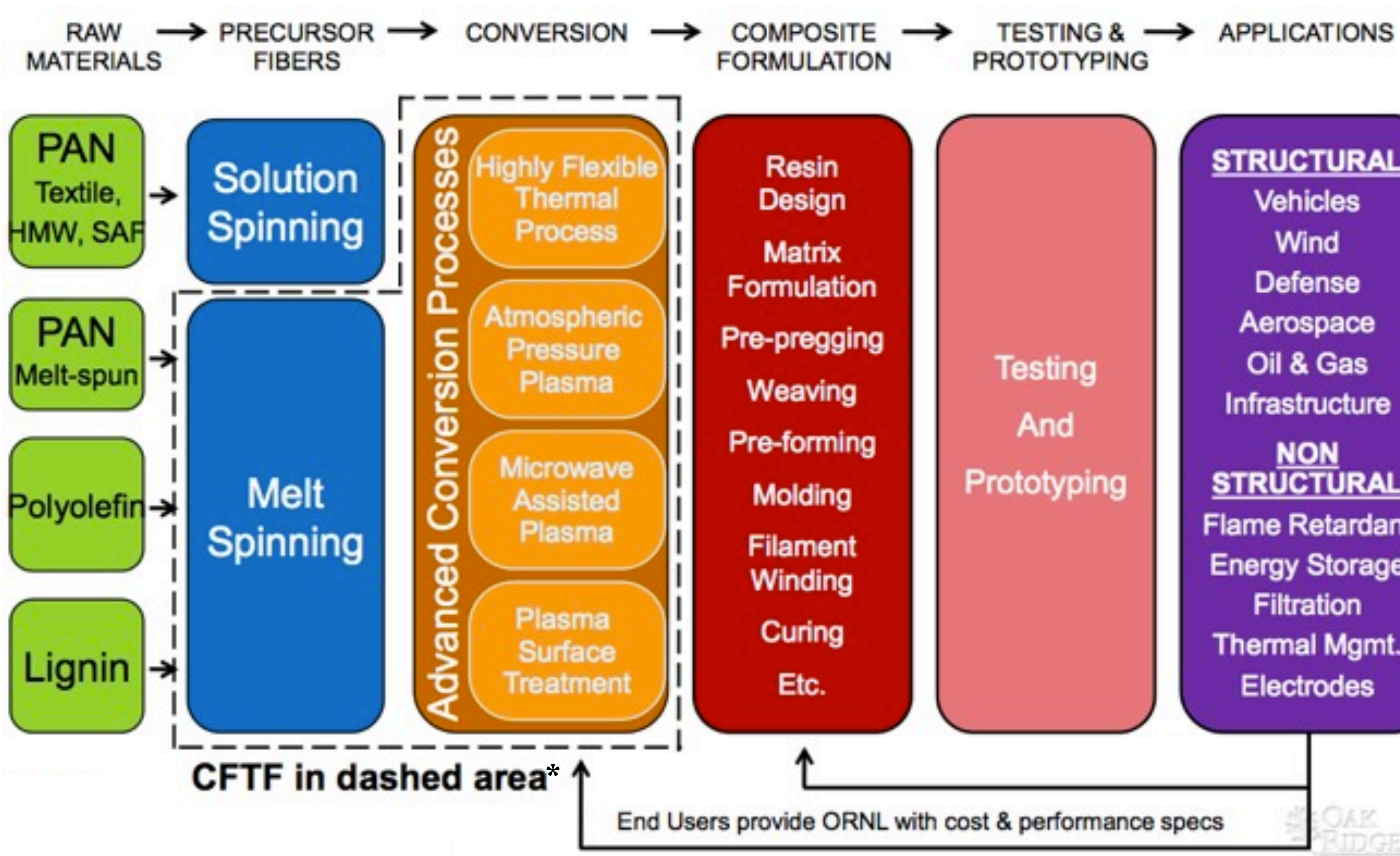
- Highly instrumented, highly flexible conventional carbon fiber line for "any precursor in any format"
- Melt-spun fiber line to produce precursor fibers
- Provisions for additional future equipment
- Produce up to 25 tonnes/year of carbon fibers
- Demonstrate technology scalability
- Train and educate workers
- Work in partnerships with industry



Facility and equipment perspective



Primary CFTF Objectives	
Demonstrate low-cost carbon fiber (LCCF) technology scalability with the last scaling step before full-scale commercial production	Produce quantities of LCCF needed for large-scale material and process evaluations and prototyping



*Advanced conversion is not within the current scope of ARRA-funded CFTF capability. The center will be equipped with conventional conversion equipment with space available for advanced processes in the future.
ORNL, DOE Vehicle Technologies Program

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Challenges

Several challenges hamper widespread adoption of automotive carbon fiber composite

Manufacturing Innovation	1. Reducing material cost a. Precursor b. Process 2. Enhancing part manufacturing a. Manufacturing processes b. Assembly processes c. Finishing
Design & Analysis Enhancement	3. Designing for performance and cost-effective producibility a. Design for unique composite material properties b. Design for manufacturability and assembly c. Design for replacability and repairability 4. Enhancing the design & analysis toolset a. CAE tools b. Material specifications and standards
Lifecycle	5. Ensuring life cycle robustness a. Repair b. Recycling

Several challenges hamper widespread adoption of automotive carbon fiber composite

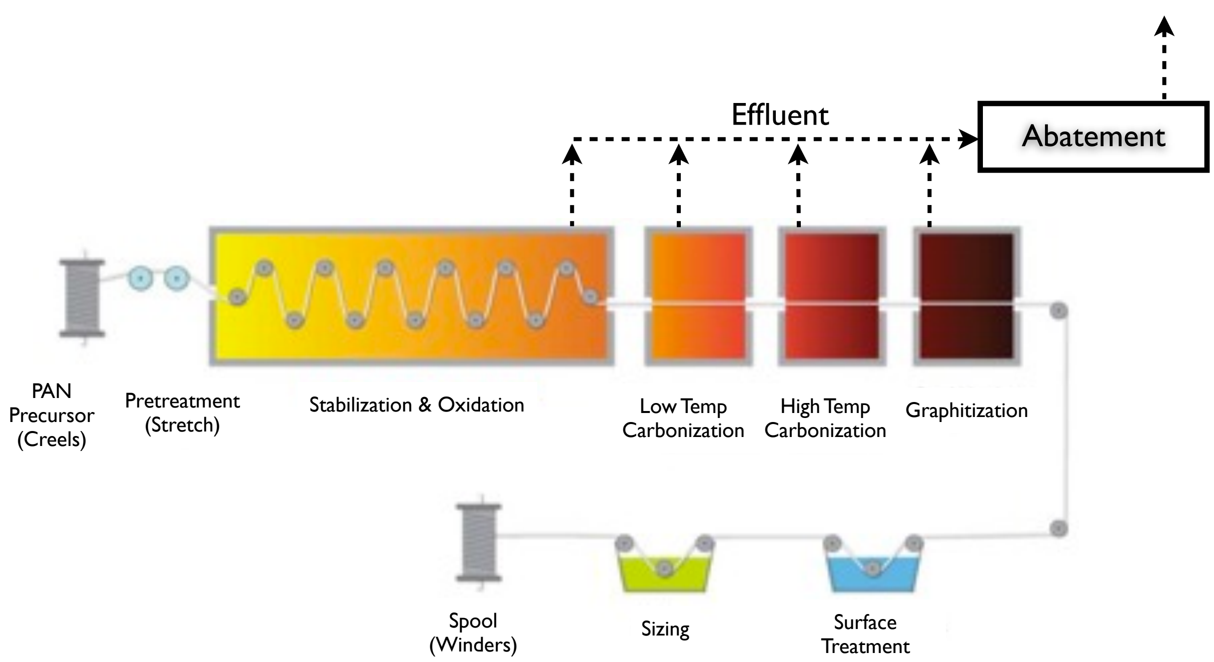
Manufacturing Innovation

1. Reducing material cost

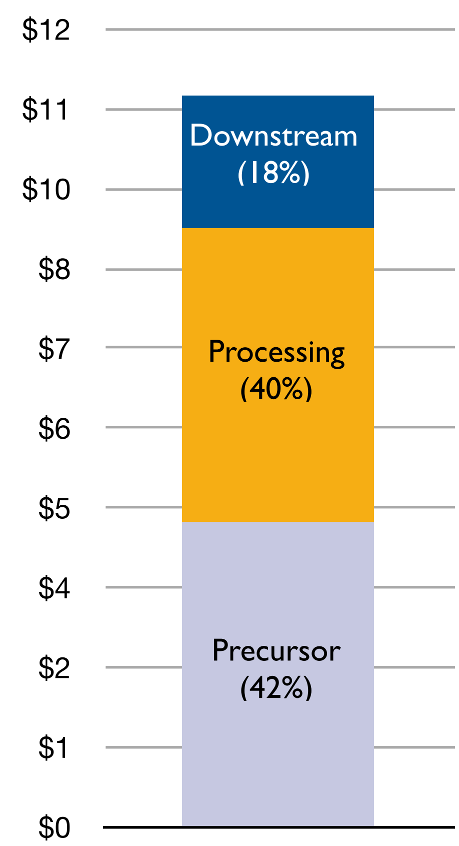
Summary

Raw material cost is the greatest driver of carbon fiber composite part production cost. In order for automotive carbon fiber composites to see more widespread adoption, material cost must come down by about 40%: from ~$11/lb to $6-$8/lb (including resin). The largest cost contributor is currently PAN precursor. Other costs include energy-intensive conversion (stabilization, oxidation, carbonization, graphitization, surface treatment, spooling, and packaging) and downstream processing (creating weave or mat, shipping, applying resin, packaging, and trimming).

Several technology pathways exist to achieve the cost competitiveness with steel-based vehicles and parts. Lower cost alternative precursors include textile-grade PAN, lignin, and polyolefin. Cost reduction is also expected from economies of scale. Significant research and development is also underway among carbon fiber producers to signifcantly reduce the time- and energy-intensity of the fiber processing steps.



Current carbon fiber cost structure

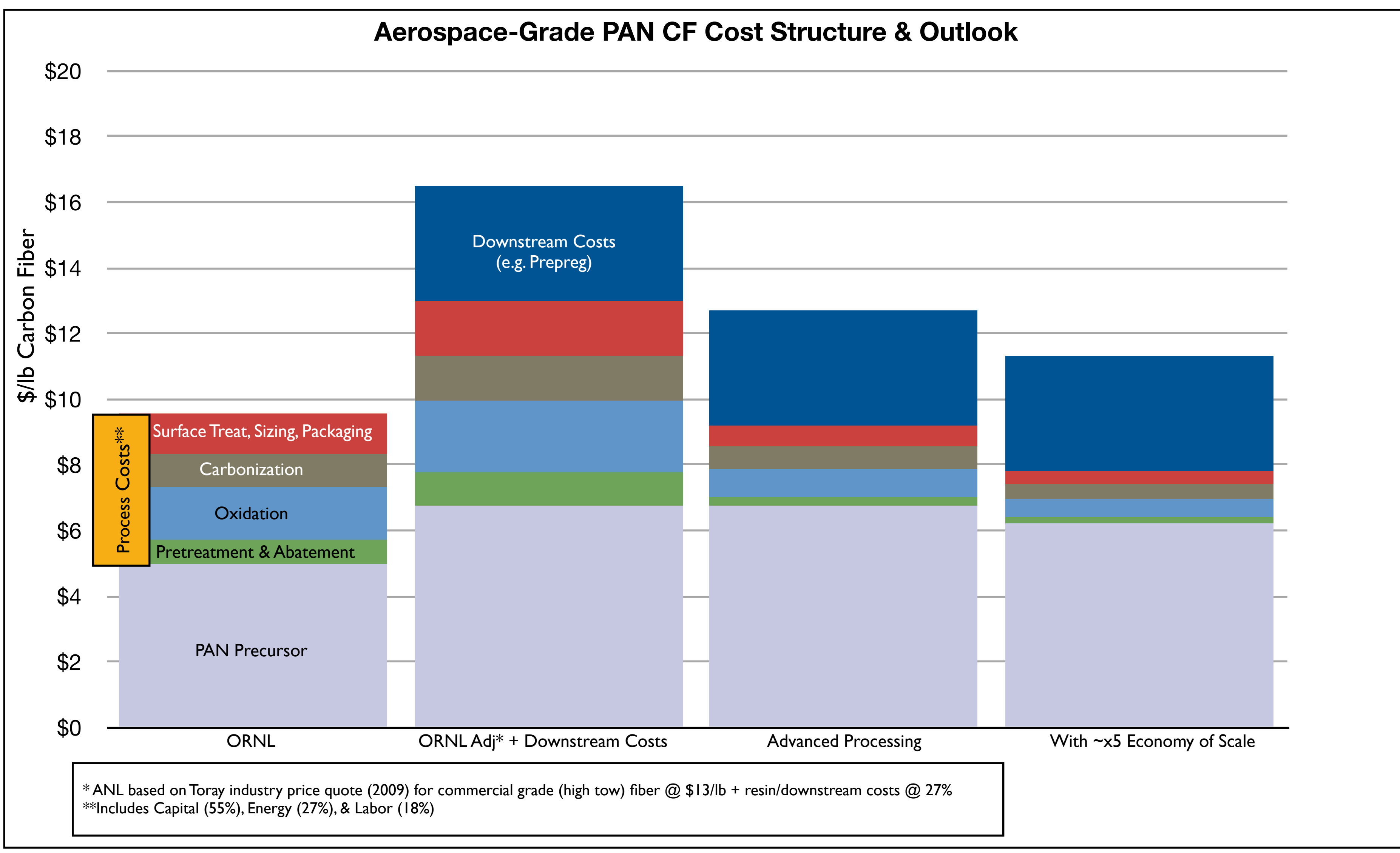


1. Manufacturing Innovation: Reducing Material Cost

1a. Precursor

Aerospace grade carbon fiber is currently produced from specialty polyacrylonitrile (PAN) precursors. The high material cost of these proprietary precursors is driven largely by the need to precisely control purity, polymer composition, molecular weight distribution, molecular orientation, and orientation of the fibers during processing steps. The better the process control with respect to these variables, the better the material properties of the resultant fibers.

Precursor	Grade	Challenge	Near-term Price	Future Price	Timeline	Min. Properties
PAN	Aerospace	Very Expensive	$16	$11	NOW	MET
PAN	Commercial	Expensive	$11	$7	NOW	MET
Textile PAN	Commercial	Fiber Properties	$8	$6	NEAR	MET
Lignin	Commercial	Fiber Properties, Blending, Stretching	$9	$6	MED	NEARLY MET
Polyolefin	Commercial	Material Properties	N/A	$6	FAR	NOT MET



Automotive application of carbon fiber composite, as compared to aerospace applications, can be considerably more varied and less demanding regarding material properties. The automotive industry can thus potentially realize significant cost savings by tailoring material requirements (and precursor quality) to various automotive applications.

The DOE Vehicle Technologies Program has thus set programmatic, automotive-appropriate material properties goals of 250 ksi strength and 25 Msi modulus. These values are partially based on prior work by the Automotive Composites Consortium, which found that parts could not be manufactured to thin enough gauge in most automotive applications to benefit from strength and stiffness in excess of these values.

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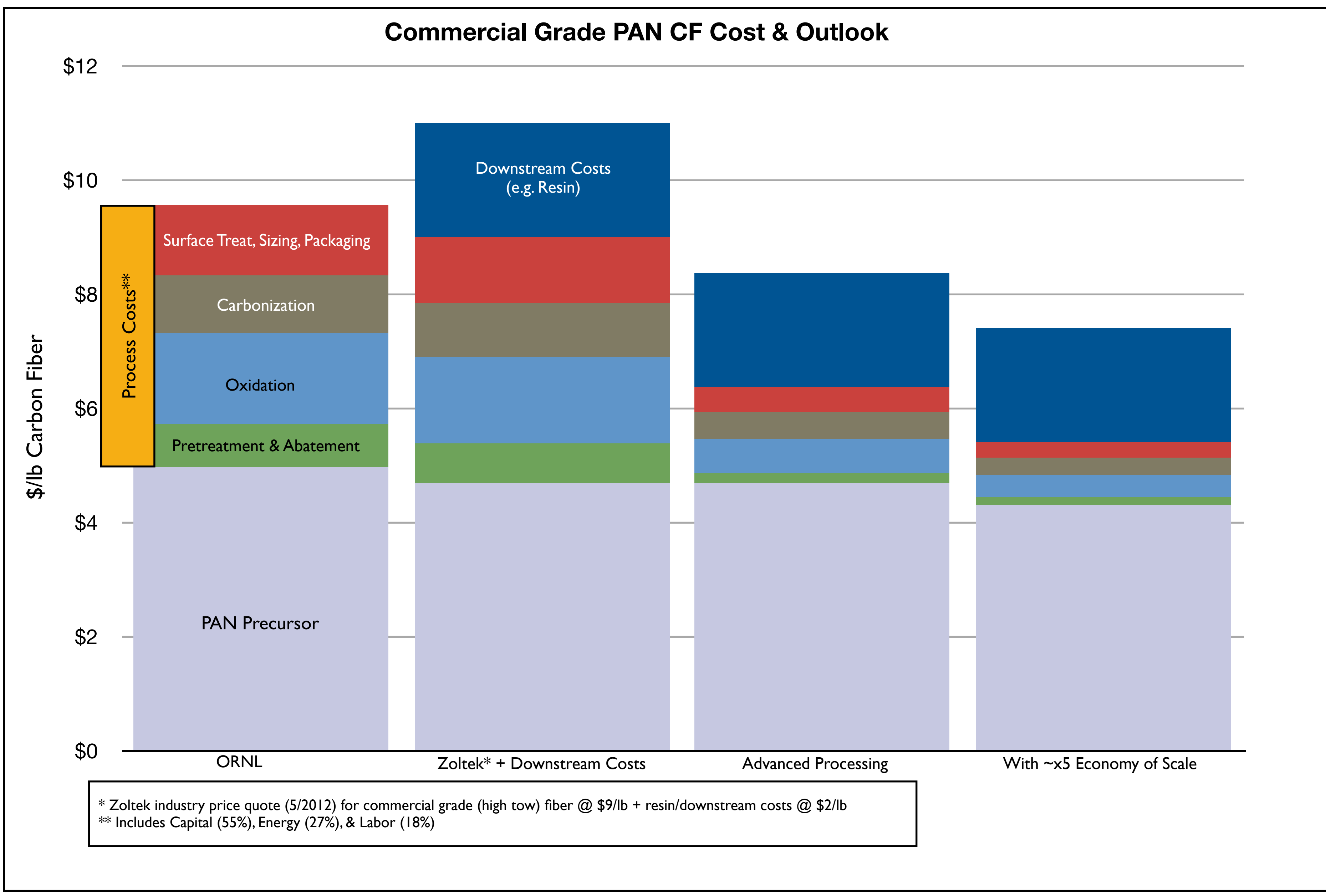
1. Manufacturing Innovation: Reducing Material Cost

Alternative Precursors

Because precursor currently comprises about half of material cost, the search, both in the public and private sector, has been underway for several years to identify alternative precursors for non-aerospace applications.

Commercial Grade PAN

Several companies, such as Zoltek, SGL, TohoTenax, and Mitsubishi produce non-aerospace-grade carbon fiber for industrial and wind applications. The key element of cost reduction that differentiates aerospace grade from other grades is tow size. Multiple filaments of carbon fiber are bundled into "tows" and categorized into sizes based on the quantity of filaments per tow. Smaller tow size tends to result in improved material properties but increased production cost. Anything below 24,000 filaments per tow (24k) is considered aerospace grade, while larger tow sizes ranging all the way up to 320k* are considered commercial or industrial grade. The adoption of larger tow sizes drives some changes into manufacturing processes that have been tailored to small tow sizes, but more and more companies are making the switch or adopting manufacturing processes compatible with larger tow sizes to capture the associated material cost advantage.



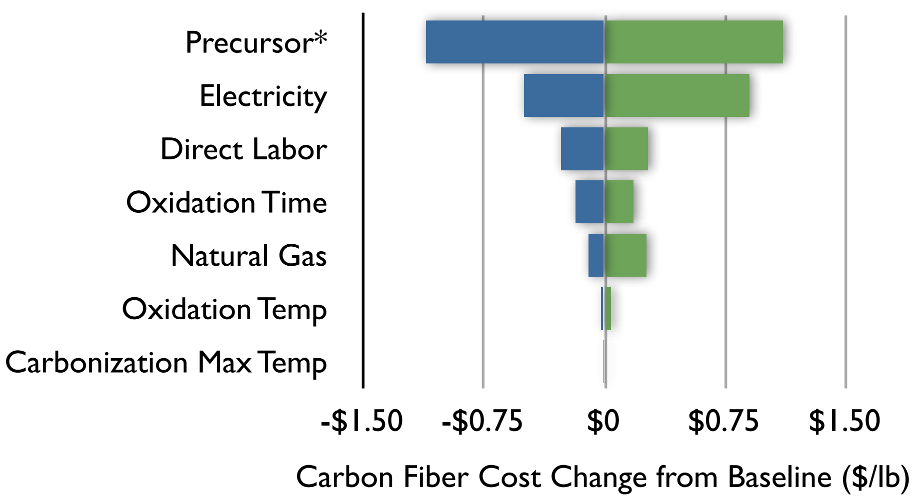
*Research is also currently underway to derive small tows from high tow bundles, a process referred to as "tow splitting". This could allow producers to benefit from the cost advantage of high tow processing while minimizing or eliminating the material property degradation associated with high tow part manufacturing.

Challenges

1. Manufacturing Innovation: Reducing Material Cost

Alternative Precursors

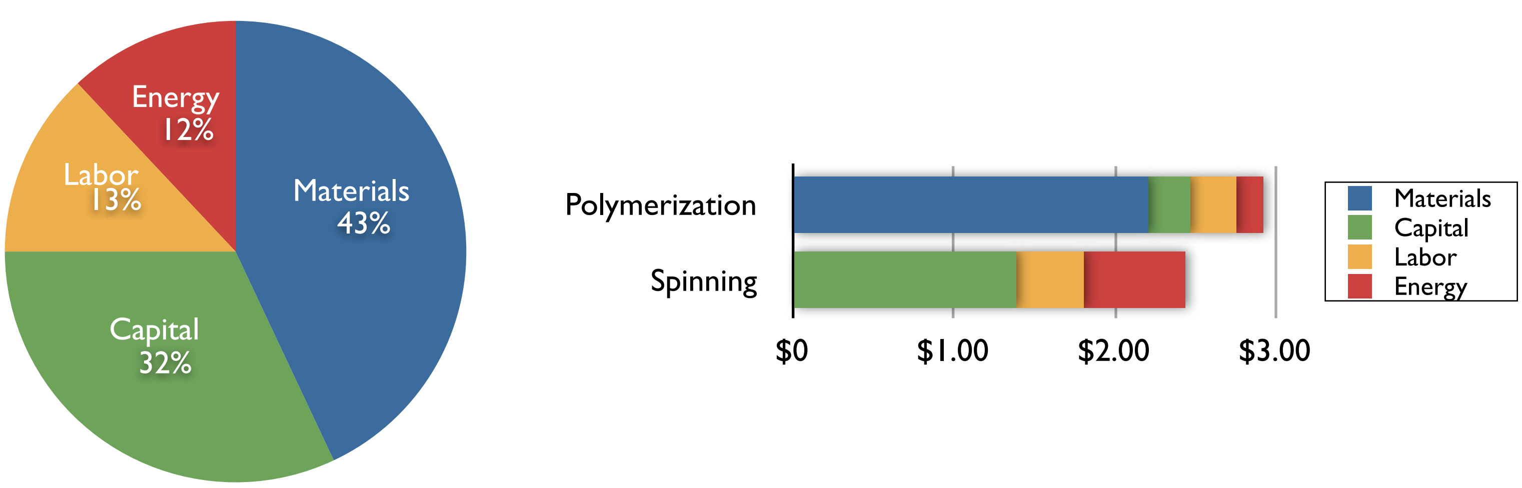
Commercial Grade PAN Carbon Fiber Cost Sensitivities



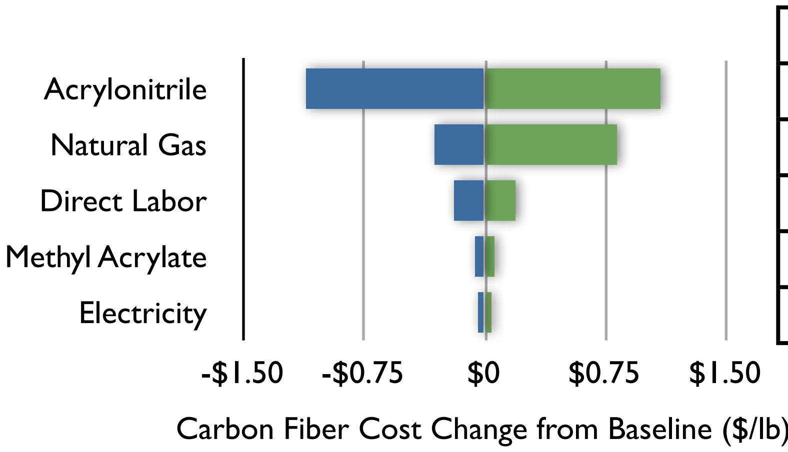
Low	Base	High
$3.96/lb	$4.97/lb	$5.98/lb
4.0¢ /kWh	6.9¢ /kWh	12¢ /kWh
$20/hr	$28/hr	$36/hr
80 min	100 min	120 min
$2/MMBTU	$5/MMBTU	$13/MMBTU
210-230°C	240-260°C	290-310°C
1100-1300°C	1300-1500°C	1500-1700°C

Commercial grade PAN precursor, despite its lower price relative to aerospace grade PAN, is the dominant cost driver. High sensitivity to electricity costs drives carbon fiber manufacturers to seek out states with low electricity rates, such as WA, WY, SC, AL, TX, and TN. See below for a closer look at the cost structure of the precursor itself.

Commercial Grade PAN Precursor Cost Structure*



Commercial Grade PAN Cost Sensitivities



Low	Base	High
$1000/t	$2200/t	$3400/t
$2/MMBTU	$5/MMBTU	$13/MMBTU
$20/hr	$28/hr	$36/hr
$1000/t	$2350/t	$3700/t
4.3¢ /kWh	6.9¢ /kWh	12¢ /kWh

Precursor cost is driven primarily by the cost of acrylonitrile, which is in turn driven by the cost of oil.

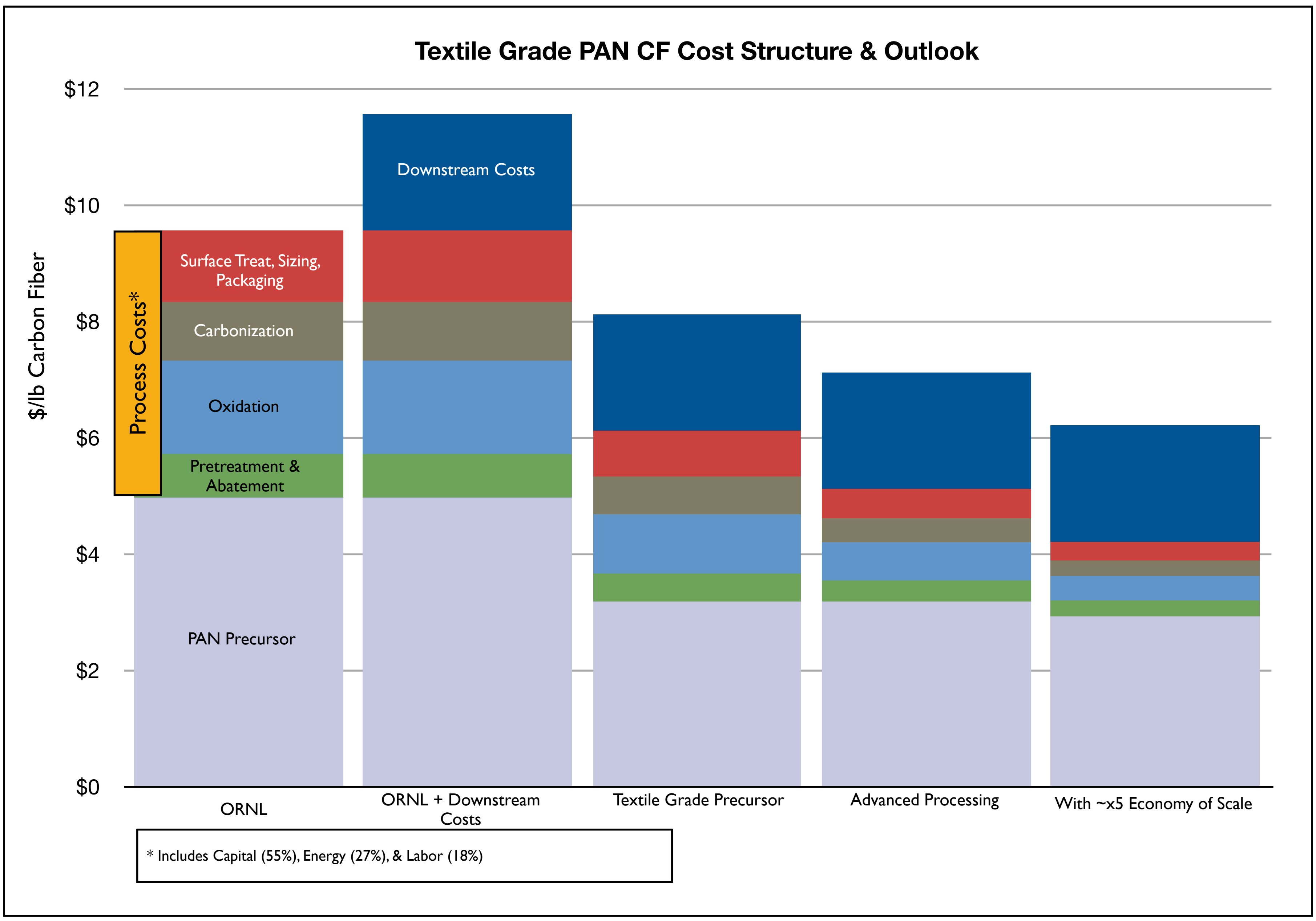
*Values are expressed as $/lb of resultant carbon fiber (as opposed to $/lb precursor). Precusor to carbon fiber conversion efficiency = 47.6%

Alternative Precursors

Textile Grade PAN

The textile industry produces in very large volumes and can thus provide an economy of scale in producing precursor. A second means of cost reduction results from the high oxygen content of textile grade precursor that potentially enables the slowest step of carbon fiber processing, oxidation, to be accelerated. Textile grade precursors can often be incorporated into existing carbon fiber facilities because their composition is close enough to that of conventional PAN that it does not require significant process modification.

ORNL is working with Fisipe SA of Portugal and has consulted with SGL & BMW to test sample quality. Textile grade carbon fiber is expected to be available as soon as 2013 and is probably the most likely near-term means of significantly reducing carbon fiber cost.



Alternative Precursors

Lignin

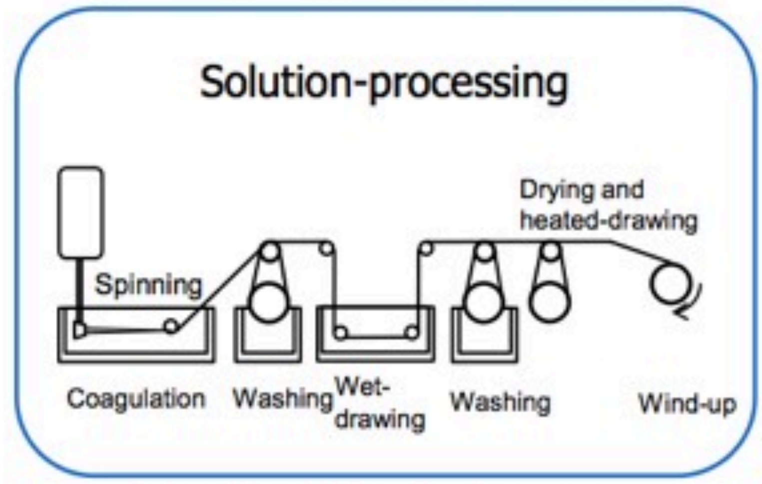
Lignin, the fibrous constituent of biomass and a byproduct of the Kraft process in pulp & paper mills, can potentially provide a lower cost precursor than even textile grade PAN, and offers the added advantage of decoupling the carbon fiber industry from the petroleum and natural gas industries.

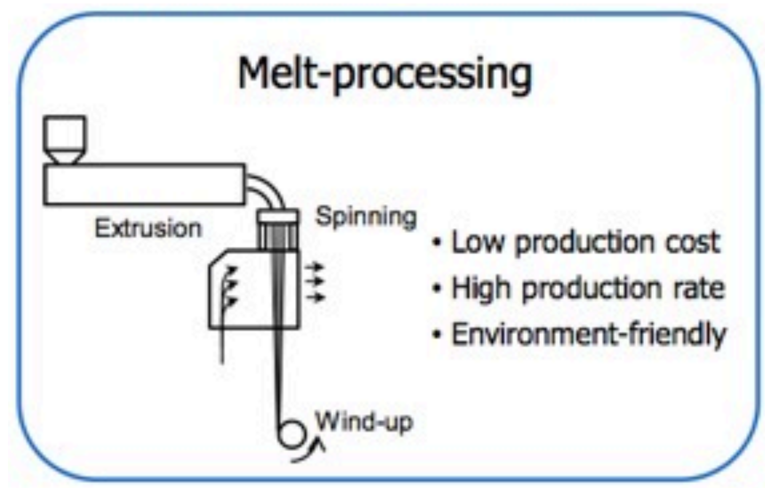
Hardwood kraft lignin can be precipitated from pulping liquors. Contaminants such as salts and carbohydrates can be removed by a combination of prefiltration, fractional precipitation, and washing. The processes for purifying and precipitating lignin from pulping liquors are cost-effective and scalable. Softwood Kraft lignin is cleaner than hardwood lignin and does not require purification as part of the precipitation and spinning process.

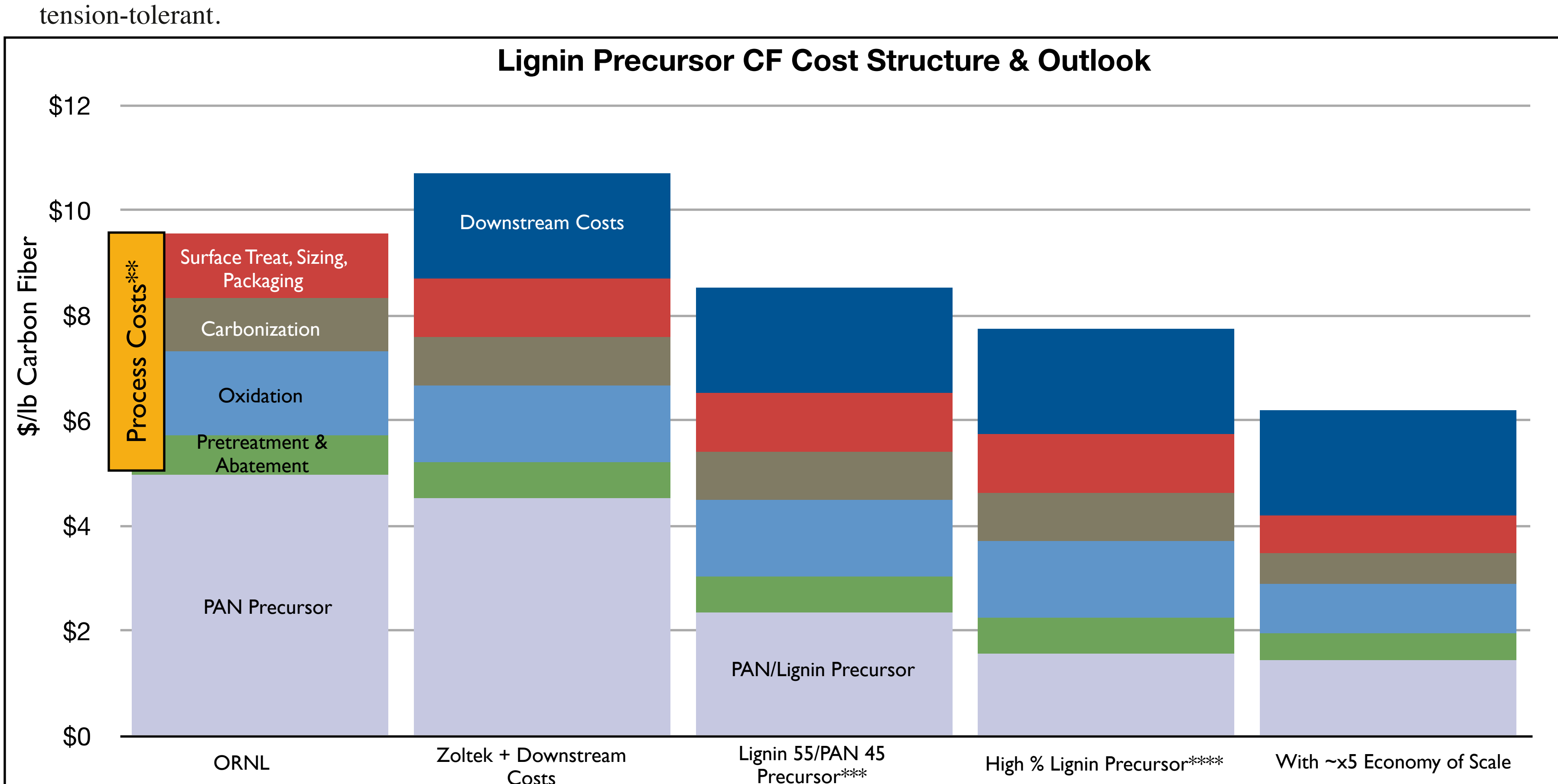
A key element of cost reduction associated with lignin precursors is their amenability to "melt spinning," (right, bottom) a much more cost-effective and less chemical-intensive process for producing precursor fibers as compared to traditional solution spinning (right, top).

MeadWestvaco Corporation and Weyerhaeuser (in collaboration with Zoltek) are the two main commercial producers of Kraft lignin products.

Zoltek is investigating Lignin/PAN blends of up to 55% lignin content. The DOE material property targets of 250 ksi strength and 25 Msi modulus have very nearly been met (244 ksi and 29 Msi for a 35/65 blend) and are expected to be met with scaled up production that results in an optimal stretching process--work remains to make the fiber more tension-tolerant.







* Zoltek industry price quote (5/2012) for commercial grade (high tow) fiber @ $9/lb + resin/downstream costs @ $2/lb
** Includes Capital (55%), Energy (27%), & Labor (18%)
***11% due to lignin substitution + 10% due to expected increase in conversion efficiency of lignin precursor + 4% due to x1.5 production speed increase = 25% total cost reduction
****20% due to lignin substitution + 10% due to expected increase in conversion efficiency of lignin precursor + 4% due to x1.5 production speed increase = 34% total cost reduction

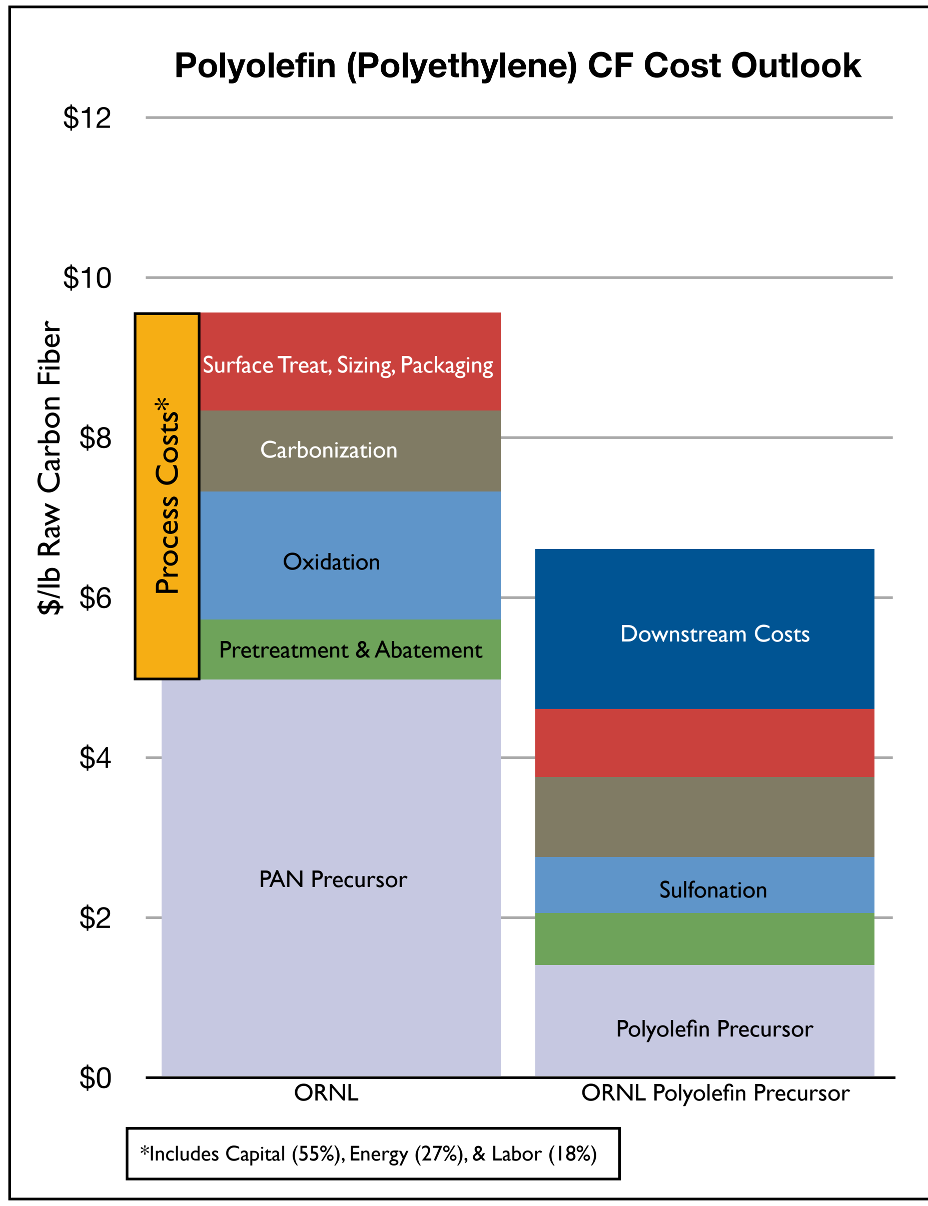
Alternative Precursors

Polyolefins

Precursor carbon content is the key determinant of yield, or how much carbon fiber is produced per unit of precursor input. Polyolefins (including polyethylene and polypropylene) contain 86% carbon by weight (as compared to PAN's 68%) and therefore offer inherently higher yield potential.

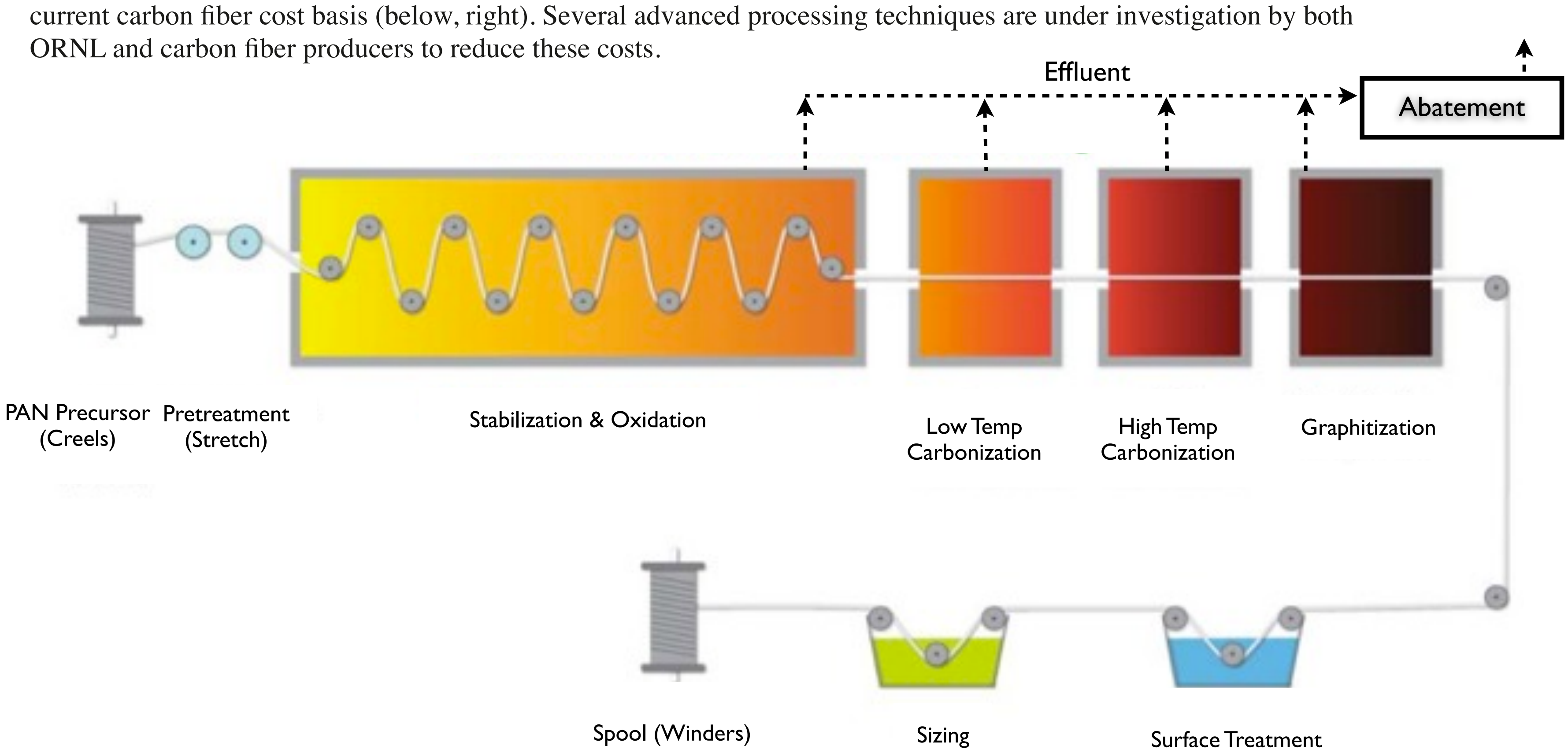
Polyolefins are also much cheaper than any of the other precursor options and offer partial decoupling from natural gas and petroleum prices because they can potentially be produced from recycled plastic trash.

Hexcel made progress with polyolefinic precursors in the early 2000s, but found challenges associated with sulfuric acid recycling and availability of precursor. ORNL—in collaboration with Dow Chemical; Hills, Inc; Fibervision; and the University of North Carolina at Chapel Hill—continued to investigate and has recently made significant progress toward DOE's material property targets of 250 ksi strength and 25 Msi modulus. The best properties achieved with the ORNL work is 201 ksi strength and 20 Msi modulus, but earlier Hexcel work showed (at small scale) that values up to 380 ksi, 30 Msi are possible. Further progress by ORNL with improved polyolefinic carbon fiber properties has been delayed due to DOE Vehicle Technologies Program budget constraints for FY2012.



1b. Advanced Processing

Conventional PAN processing (below) involves several energy- and time-intensive processes that drive 40-50% of the current carbon fiber cost basis (below, right). Several advanced processing techniques are under investigation by both ORNL and carbon fiber producers to reduce these costs.



Stabilization & Oxidation

Thermal stabilization and oxidation are currently the rate-limiting steps of the conversion process, currently accounting for 80% of total processing time. Three to four successive furnaces are used at 200-250°C.

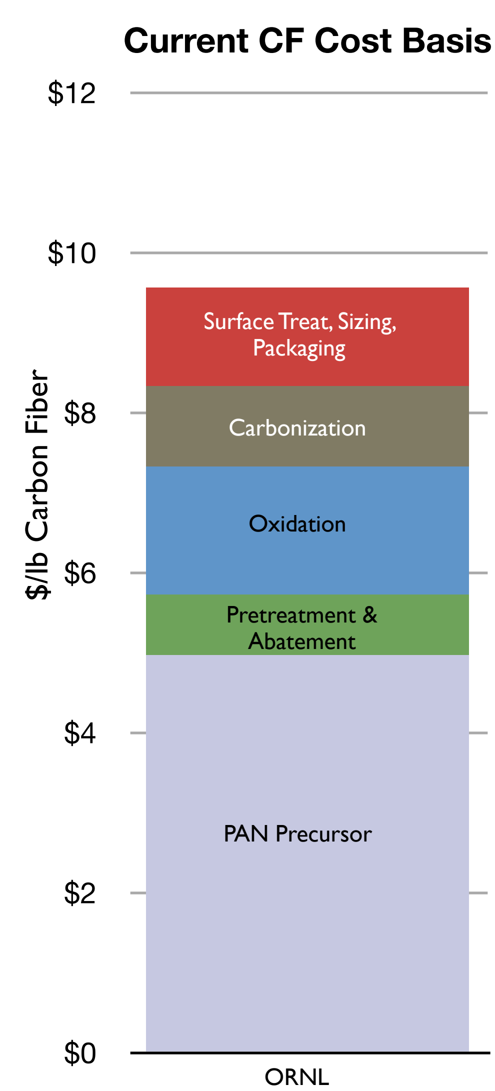
ORNL has investigated advanced methods such as electron beam, ultraviolet, and thermochemical-based plasma for PAN-based precursors. The plasma process appears to offer the greatest cost reduction potential. ORNL's Advanced Stabilization process would replace the first of four furnaces used in conventional stabilization, and the Advanced Oxidation process would replace the final three furnaces. ORNL has seen reduction in residence time in the thermal oxidative stabilization ovens from 90-120 minutes to 35 minutes.

Carbonization & Graphitization

The most promising technology identified by ORNL for replacing the high- and low-temperature carbonization ovens used in conventional processing for PAN-based precursors is microwave-assisted plasma (MAP). It can be applied to textile grade PAN precursor if chemically treated.

The MAP process is particularly advantageous for automotive (or industrial) grade fibers with tow sizes in excess of 48K: reduced carbonization oven residence time, lower capital investment and energy demand, lower operation temperatures, better equipment start-up and shut-down times, and lower hazardous emissions and assocated emissions treatment requirements. The MAP process also enables controlled surface chemistry which can lend improved composite material properties.

The MAP process has the potential to reduce PAN-based carbon fiber cost by ~$1/lb, a 20% reduction in processing cost.



Sources: ORNL 2012; Rehkopf 2012

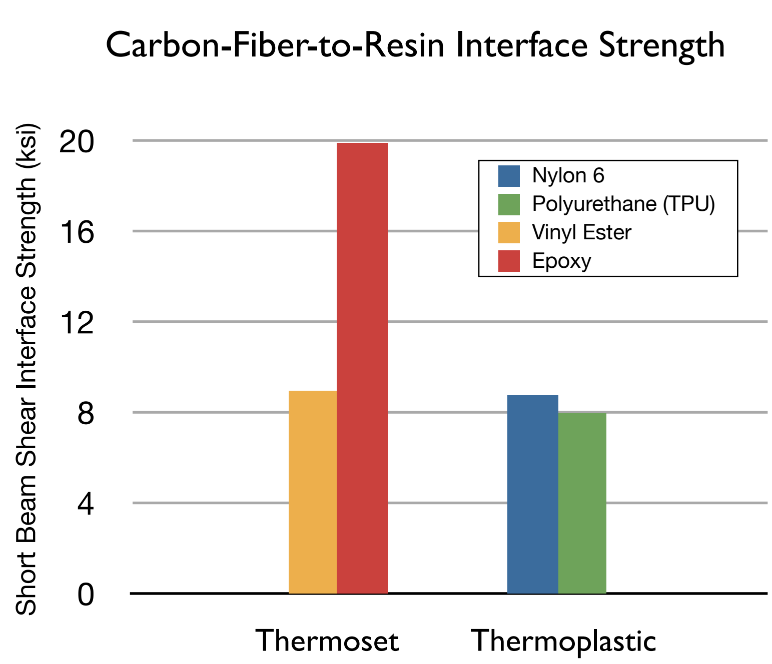
Resin Overview

Common aerospace epoxies (thermosets) require 30 minutes or more to cure. Faster-curing epoxies have become available, and other thermosetting resins such as polyurethane have been developed. As an alternative to thermoset, thermoplastic resins do not require a curing stage and can thus provide very rapid cycle times.

Resin	Advantages	Challenges	Cure Time	Tunability
Epoxies	well-studied, workability	High viscosity, expensive	generally slow	high
Polyesters	processibility, dimensional stability			high
Vinyl Esters	tough, low corrosion	Shrinkage	fast	low
Polyurethanes	tough, low corrosion	High viscosity	fast	low
Phenolics, Bismaleimides, Polyimides	high temp resistance			low
Thermoplastics	processibility, remeltable, does not require curing, tough, high strain to failure	temp resistance, interfacial bond strength	N/A	high

Interfacial Bond Strength

With certain resins, low interfacial bond strength at the fiber-resin interface is the limiting factor regarding the part's ability to withstand load. The interface bond strength can thus erode the strength advantage of carbon over other types of fiber and prevent the processing advantages of particular resins from being captured. Fiber surface morphology is largely determined by the surface treatment step of fiber processing, underscoring the importance of matching downstream resin types with upstream fiber surface treatment methods.



ORNL; DOE Vehicle Technologies Program; Rekhopf, Jackie D *Automotive Carbon Fiber Composites: From Evolution to Implementation* 2012.

Resin Types

Thermosets

Thermosetting plastics, commonly referred to as thermosets, are characterized by an irreversible cure process. The molecular reaction that occurs during cure results in a cross-linked structure with higher molecular weight, and therefore a higher melting point, than the liquid reactant. The melting point of the product of reaction eventually climbs above the temperature of the ambient environment, thus resulting in solidification. The melting point climbs so high, in fact, that it exceeds the degradation temperature of the material, thus precluding the possibility of melting to recover the fiber (recycling is discussed in following section) or to re-shape the part.

Epoxies

The most common epoxies used in composites manufacturing (primarily in aerospace) are glicidyl ethers and amines with cure times usually in excess of 30 minutes. While it is possible to tweak and tailor epoxy to meet the variable demands of automotive applications, epoxy's high viscosity usually limits its use to particular manufacturing processes (discussed in the next section), such as molding, filament winding, and hand layup. Curing agents can be mixed with the epoxy to significantly increase cure time to meet demanding cycle time requirements, but the resulting chemical reaction can adversely affect fiber-resin adhesion and part quality. Epoxies exhibit relatively low shrinkage of 3-4%.

Unsaturated Polyesters

Polyesters generally cure faster than epoxies. Variable formulation of unsaturated polyesters enables tailorable viscosity (which controls fiber wet-out), reactivity (which controls cure time and exotherm properties), resiliency, and heat deflection temperature. They exhibit high dimensional stability and are among the more affordable resins. They can also be formulated to be corrosion resistant and fire retardant.

Vinyl Esters

This resin type was developed to provide the workability of epoxy and the fast curing of polyesters. In terms of both material properties and cost, they represent the middle ground between epoxies and polyesters. They exhibit particularly high corrosion resistance and toughness, but can present dimensional stability challenges by shrinking by as much as 10% during curing.

Polyurethanes

Known from high-performance paint coatings and floor coverings, polyurethanes are very tough and corrosion resistant. They are often applied in 2 part mixtures that exhibit very high cure times and increased viscosity upon mixing. Becuase of these characteristics, their application is usually limited to small parts (usually in reaction injection molding processes) or continuous processes such as pultrusion.

Phenolics, Bismaleimides, and Polyimides

These resin types have been used in aerospace (composite bypass ducts on fighter jet engines) because of their high temperature resistance. High-temp automotive applications, such as under-hood, may require the use of one of these thermoset resins.

Thermoplastics

Thermoplastics that can be incorporated in carbon fiber composite include polypropylene (PE), polyamide (PA or nylon), acetal, acrylonitrile butediene styrene (ABS), polyethersulfone (PES), polyetherimide (PEI), polyetheretherketone (PEEK), polyetherketone-ketone (PEKK), and polyphenylenesulfide (PPS). They are characterized by a reversible, low-temperature consolidation process involving melting and re-solidifying. Unlike in thermosets, the chemical bonding structure is not crosslinked in thermoplastics, but rather characterized by weaker intermolecular (i.e. van der Waals) forces.

In general, thermoplastics are easier to process and have better toughness and strain-to-failure characteristics than thermosets. In particular, they do not need to be cured and thus often exhibit faster cycle times than many thermosets.

Thermoplastics often exhibit lower interfacial fiber-resin bond strength (see chart on previous page), but carefully matching the fiber grade and resin type to the application can help designers avoid specifying overly-strong (and needlessly expensive) fiber.

ORNL; DOE Vehicle Technologies Program; Rekhopf 2012.

1. Manufacturing Innovation: Reducing Material Cost

Intermediate Materials & Processes

Depending on the intermediate reinformcement form of the fiber, several intermediate materials come into play and make a contribution to the material cost structure (categorized as "Downstream Costs" on the raw material cost structure graphs of pp 15-20).

Binder

In prepregs, the binding intermediate material is the resin itself, used both to hold the fibers together for easy handling and to provide the resin for the final part manufacturing process. Smaller amounts of binder are also used even for non-prepregs that will be wet-processed. Surface treamtment, the final step of raw fiber processing, often includes application of an intermediate epoxy or another custom material to enhance interfacial bond adhesion between the fiber and the resin.

UniDirectional Tape

Unidirectional (UD) tape is a form of prepreg with fibers all aligned in one direction along the length of the tape. For thermoset-based UD tape, a polymeric backing is applied to keep the fibers aligned and to allow the tape to be wound onto a roll without layers bonding together. Thermoplastic-based UD tape does not require a backing, as the material is not tacky at room temperature.

Stitches, Weaves, and Knits

A polymeric thread or lightweight fiber is used to hold bundles of fiber together in various configurations. Non-crimp fabrics allow carbon fibers to stay in-plane and aligned and are often referred to as "stitched fabrics." These fabrics can be made of a single layer or multiple layers of various orientations (e.g. 0/90, ±45, 0/±45/90) all stitched together.

Strechable knitted fabric consists of insertions of wefts or warps to keep the fiber in parallel across the whole width of the fabric.

Woven fabrics consist of interlacing sets of orthogonal fiber bundles produced on a loom. Different tow sizes can be used in different orientations in this arrangement. Most woven carbon fiber fabrics are 2D woven fabrics, but a few companies have worked on creating 3D weaves that eliminate interlaminar weakness characteristic of 2D fabrics and that allow more complete, net-shape preforms to be woven directly on a loom. Weaves are usually used as preforms in liquid molding processes. However, dry woven fabrics are also commonly converted to thermoplastic prepreg (called reinforced thermoplastic laminates ("RTL") or "organosheet") or thermoset prepreg.

During the textile processing, multiple reinforcement types can be combined (e.g. glass and carbon fiber). With thermoplastics, sometimes a textile form of the resin is commingled with the reinforcement fiber or woven in with the reinforcement to create a dry preform.

Braids

Braided fiber can be dry or pre-pregged and can be done in 2 or 3 dimensions. Complex braiding machines interweave multiple threads to create solid, tubular, or flat sections. The most well-known example of braided carbon fiber in the automotive industry is the A-Pillar of the Lexus LFA.

Core Material

A common composite construction for carbon fiber is a sandwich panel consisting of face sheets of carbon fiber composite bonded to a foam, wood, or honeycomb internal core. This is a cost-effective way to increase the cross-section's second moment of area (and thus to increase its bending stiffness) because carbon fiber composite is used sparingly (at the top and bottom) where it carries most of the load while the less-expensive core material serves primarily to prevent buckling and transfer bending load into the face sheets. Commonly used core materials include polyvinylchloride (PVC), polyurethane, polyethylene, polystyrene foams, polypropylene, polyetherimide, aramid, aluminum, balsa wood, and syntactic foams.

Rehkopf 2012; The Boeing Co, Braider

Manufacturing Innovation

2. Enhancing Part Manufacturing

Summary

Manufacturing composite parts and subassemblies can be technically challenging, particularly time-consuming, and/or materially wasteful. These challenges can drive significant cost into the production process and thus weaken the value proposition associated with substituting carbon fiber composite for existing metal parts.

Cycle times for composite parts are currently too long to meet the throughput needs of current generation auto manufacturing plants. A typical 250,000-units-a-year auto plant makes a vehicle about every two minutes. This is driven in part by the fact that only half of a typical auto's retail price is manufacturing cost; the other half is fixed overhead, both plant and corporate. If production volume drops, overhead costs per auto rise and profits plunge.

While composites potentially enable cheaper fixed tooling (as compared to the dies and presses associated with steel-based manfacturing) and lower variable costs due to fewer assembly stations and robots, longer per-part cycle times in many cases require that parallel manufacturing lines be installed, thus eroding the fixed and variable cost reduction potential associated with composites.

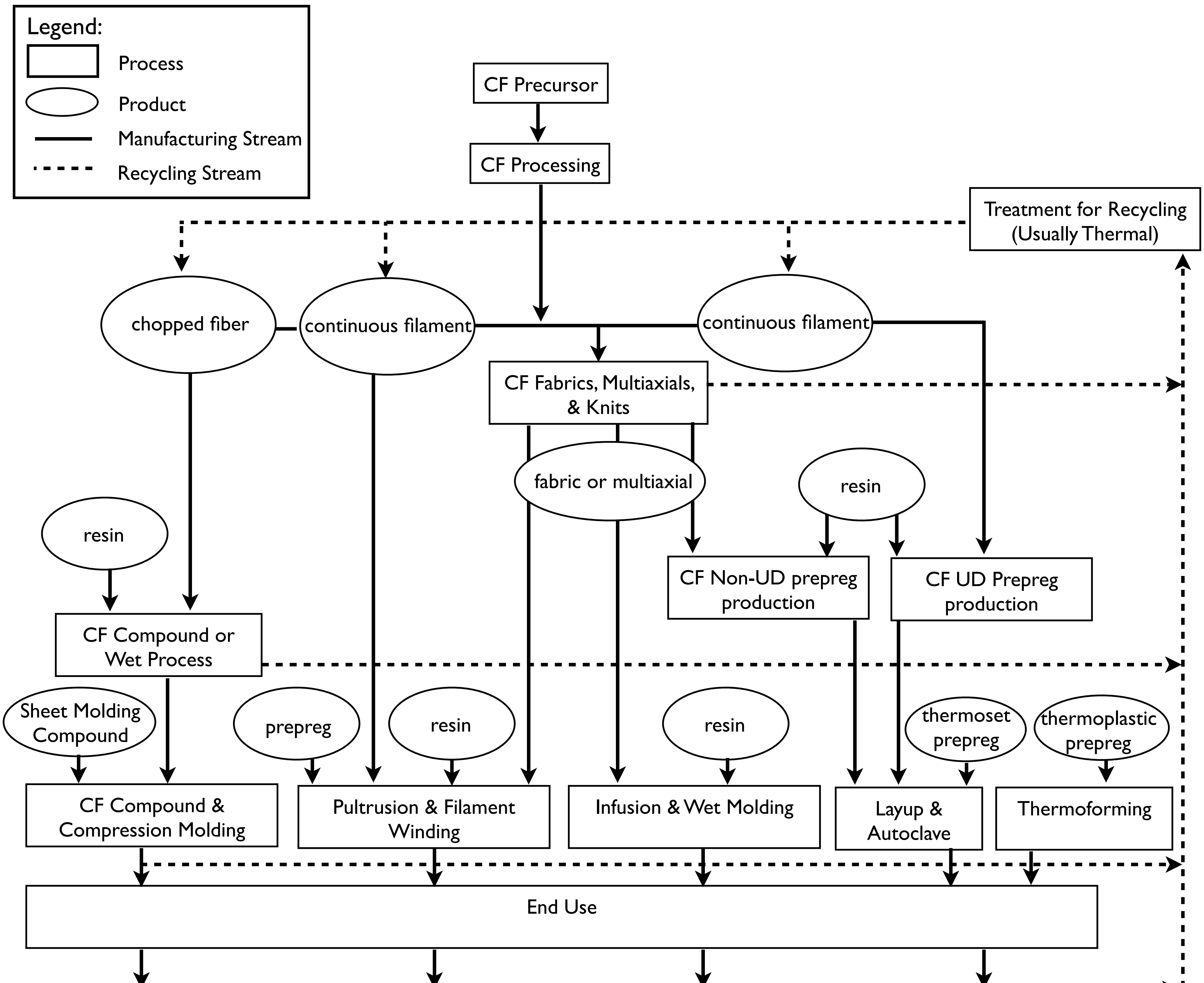
Attaching composite parts to the rest of the vehicle usually requires specialized bonding and joining processes, which must be carried out in a way that maintains the structural advantage of the carbon fiber part (i.e. by avoiding drastic differences in structural properties between the joined parts), retains a strong and durable joint, does not induce challenges associated with dissimilar material interfaces (such as galvanic corrosion and coefficiencts of thermal expansion), and fits within the OEM assembly process without undermining the vehicle production rate.

A key means of improving cycle time is to develop new tooling and processes that expand design possibilities and freedom.

Non destructive evaluation (see subsection under Section 5a: Repair) is another enabler of advanced manufacturing techniques becuase it is a key element of quality control. This will be particularly important as the speed of manufacture increases with scale production.

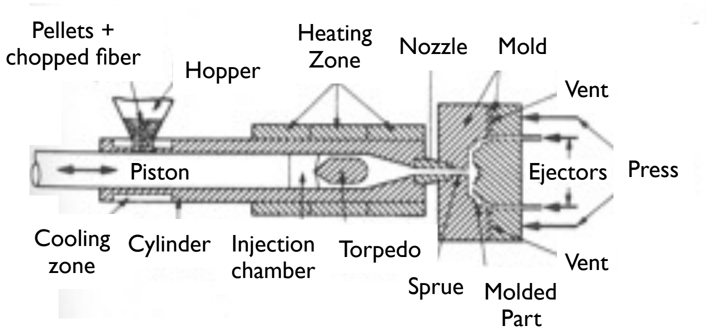
2a. Carbon Fiber Composite Part Manufacturing Processes

The aerospace industry uses a process whereby prepreg (carbon fiber preimpregranted with resin), usually epoxy-based, is cured for 30 minutes or more in an autoclave. Given the long cycle time associated with this process, several alternative "out of autoclave" processes have been developed that are more likely to meet the high-volume demands of the mainstream automotive industry, including pultrusion, compression molding, injection molding, in-line compounding, resin infusion or transfer molding (RTM), filament winding, spray forming, and thermoforming.



2a. Carbon Fiber Composite Part Manufacturing Processes

Injection Molding



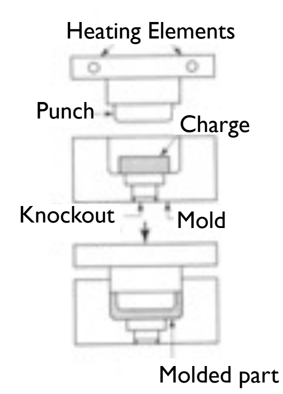
Fiber reinforced pellets of resin are first manufactured in a separate extrusion process (not shown) by feeding discrete lengths (0.25 in or less) of fiber in to melted resin, then pulling the reinforced resin through a die and pelletizing the material. These pellets are then fed into a hopper (left) and injection screw where they become melted under controlled temperature, pressure, and time conditions. The melt is subsequently injected into a mold cavity where it cools and solidifies. The majority of injection molding processes use a thermoplastic resin due to its lower cost to achieve the desired material properties.

Direct Compound Molding

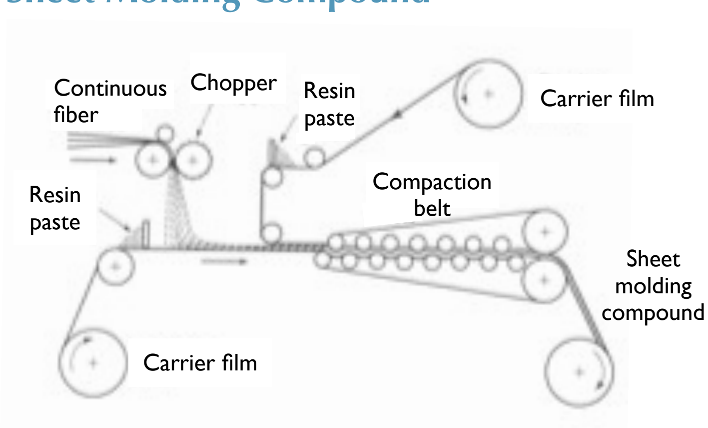
In a long fiber thermoplastic (LFT) process, resin and long (0.25-1 in) fibers from an in-line compounder are fed into a mixing extruder. The mix is either injection molded or produces a plaque that will be consolidated through compression molding. Because longer fiber lengths in the finished part lead to better material properties, even longer fiber lengths of up to 3 in have been achieved through in line compounding, often referred to as direct long fiber thermoplastic or DLFT. More complex part shapes tend to be less amenable to longer fiber lengths. Fiber attrition, or breakage during molding, is a key challenge of DLFT. Efforts are underway by the Automotive Composites Consortium to perfect and scale the use of carbon fiber DLFT for automotive applications.

Compression Molding

Typical compression molding uses thermoset-and-glass-based sheet molding compound (SMC, described below) compressed in metal die. The automotive and carbon fiber industries, including the Automotive Composites Consortium and the GM-Teijin partnership, have recently been pursuing thermoplastic-based carbon fiber sheet molding compound as a means of achieving high-volume manufacturing at low cost.



Sheet Molding Compound

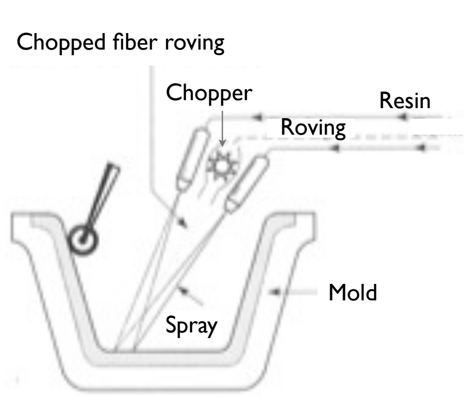


SMC is made by dispersing discontinuous strands of fiber on a bath of resin. A resin paste is applied to the top layer and a plastic carrier film sandwiches the mixture for easy handling. The sheet is then stored in a roll and matured until ready for use.

Direct Sheet Molding

SMC can also be processed immediately upon formation in a process that combines the SMC production and compression molding processes into one production line.

Spray Forming



Resin is sprayed into an open mold cavity while chopped fibers are dispensed within the spray. Recent developments have allowed continuous fibers to be sprayed.

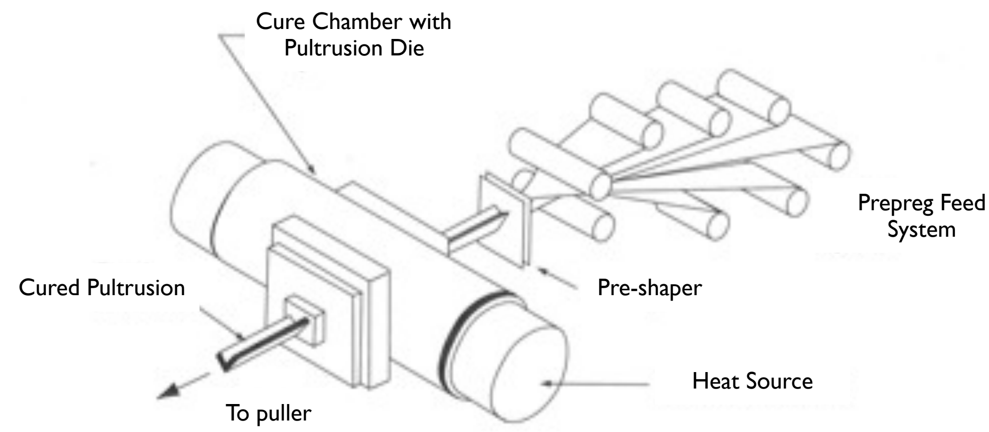
Kalpakjan and Schmidt 2007, Rehkopf 2012

2. Manufacturing Innovation: Enhancing Part Manufacturing

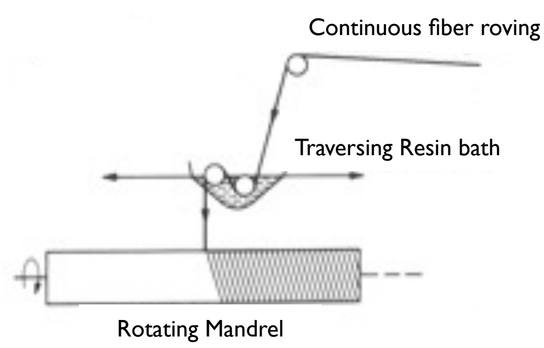
2a. Carbon Fiber Composite Part Manufacturing Processes

Pultrusion

During pultrusion, preimpregnated fiber(prepreg) is fed through a pre-shaper and then through a heated chamber that consolidates the resin and reinforcement. Alternatively, dry fibers can be pre-shaped and then resin can be impregnated just before heat is applied.



Filament Winding



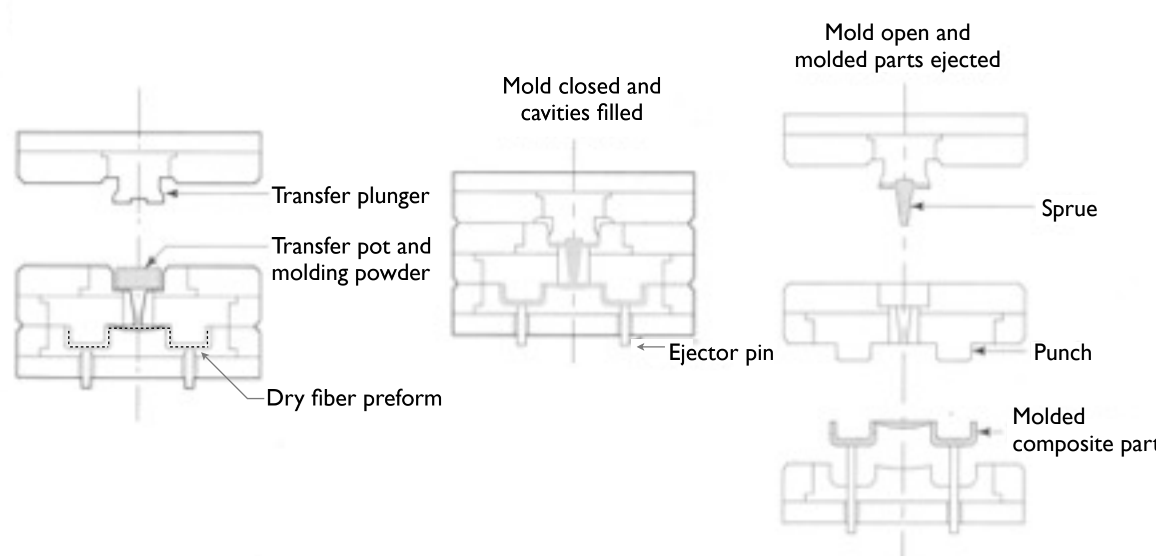
A fiber application machine places fiber on a mandrel in a predetermined orientation. Thermoset systems typically use a resin bath just prior to application on the mandrel but can also utilize prepreg to eliminate the resin bath. Another application of filament winding is to make a dry pre-form which is then impregnated with resin in an infusion process like resin transfer molding (RTM). For thermoplastic systems, prepreg can be applied to the mandrel as it is heated to consolidate the composite.

Resin Infusion

A dry reinforcement is placed in position and closed in a mold. Resin is then injected into the mold, usually at relatively low pressure, although high-pressure RTM methods are currently under investigation by toolmakers such as Krauss Maffei, Diffenbacher, and Fraunhofer ICT. The resin is typically a two part epoxy that is mixed just prior to injection.

In a variation known as reaction injection molding (RIM), catalysts and resin are injected separately and they react within the mold instead of the dispensing head. Structural RIM (SRIM) is used to produce parts that don't require a Class A finish.

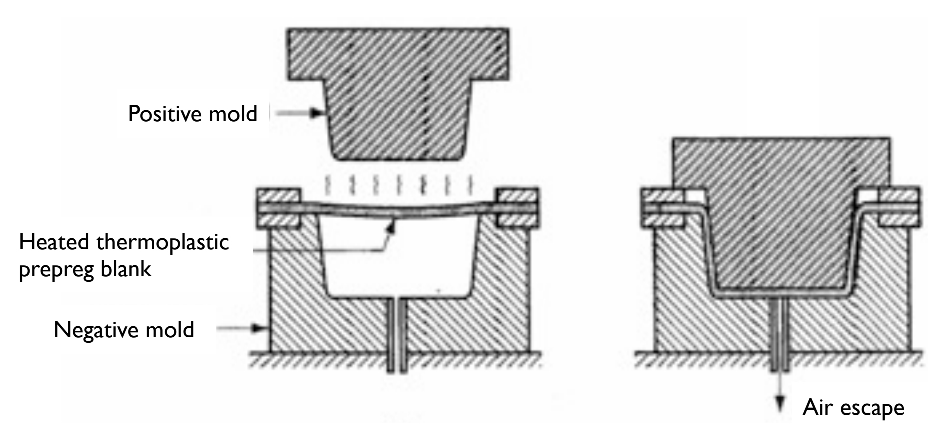
Other forms of resin infusion are vacuum assisted resin transfer molding (VARTM) which uses a vacuum mold to assist with resin flow, and high pressure injection RTM (HP-RTM) which utilizes a combination of vacuum very high pressure (60-100 bar) resin impregnation.



Thermoforming

A flat thermoplastic sheet is heated and deformed to the desired shape. The process can be applied to carbon fiber thermoplastic prepreg stacked into "blanks" (usually multilayered layups of unidirectional prepreg with each layer in a different fiber orientation). Blanks can be "tailored" such that fiber orientations of successive layers provide stiffness and strength where needed while minimizing material usage and waste.

Means of deforming the heated blank include mechanical thermoforming (shown at right), vacuum thermoforming (or simply "vacuum forming") in which negative pressure is used to pull the sheet into the mold cavity, and pressure thermoforming in which positive pressure is used to force the heated prepreg onto the mold cavity.



Kalpakjan and Schmidt 2007, Rehkopf 2012, www.sinotech.com, FiberForge

2b. Carbon Fiber Composite Part Assembly Processes

Machining

Composite parts are manufactured to near-net-shape, but almost always require machining to trim edges and attain final dimensions and edge profile for assembly. The abrasive, inhomogeneous, anisotropic characteristics of carbon fiber composites entail alternative machining proceses than those used for metal. Mechanical cutting can cause internal voids due to fiber pullout and create a heat-affected zone that melts the resin and induces microcracks. Nonmechanical cutting processes such as electrical discharge (EDM), ion beam/electron beam cutting, and microwave cutting can present challenges for carbon fiber composite as well due to high sensitivity to heat-affected zones, low electrical conductivity, and the challenge of thick sections. To maintain cut quality at prescribed production rates, expensive cutting tools that provide long tool life and good cut surface quality, such as polycrystalline diamond, must be selected.

Alternatives to mechanical cutting applicable to carbon fiber composites include abrasive waterjet cutting, abrasive cryogenic jet cutting, and laser cutting.

Joining

Carbon fiber composites must be joined to the rest of the vehicle in a way that does not undermine material characteristics or production rates. The performance and cost of the joint are also key considerations. Fasteners require pad-ups around holes to compensate for material property degradation resulting from breaching the reinforcement, so non-fastener methods such as adhesive bonding and co-curing have garnered particular interest in the automotive industry. Mechanical fasteners will nonetheless continue to play a key role, as they do in aerospace, for parts that will need to be repaired or replaced during service.

The Aston Martin Vanquish and limited-edition BMW M3 are examples of models that have successfully implemented adhesive bonding of carbon fiber composite parts in production. Adhesive bonding can be automated with robots which apply the bead and often utilize a hot air system to accelerate the cure.

Joining composites to other materials such as steel, aluminum, and plastic (each with its own interfacial properties) as part of a mixed material solution (see p. 7) must improve to enable high-volume production. In particular, the effects of thermal cycling, fatigue cycling, creep, and environmental effects on the durability of joints are currently poorly understood. As a result, expensive qualification is often required for each application.

Joint Type	Advantages	Challenges
Microwave Adhesive Bonding	fast cure rate, good mechanical properties, no residual stress	
Electron Beam Adhesive Bonding	fast cure rate, good mechanical properties, no residual stress	slow to develop commercially
Weld Bonding	very rapid	high heat intensity, still in R&D phase
Mechanical Fasteners	amenable to disassembly for repair and replacement	managing stress concentrations and clamp force, heavy, galvanic corrosion, thermal expansion, creep, delamination, water intrusion
Rivets	simple, amenable to fast automation	Same as mechanical fasteners

DOE Vehicle Technologies Program 2012, Kalpakjan and Schmidt 2007, Rehkopf 2012

2c. Carbon Fiber Composite Finishing Processes

The paint shop is the biggest investment and one of the most complex operations associated with an auto plant–"class A" is a famously stringent standard for surface finish. Carbon fiber composite surface morphology and reactivity differs substantially from that of metals and varies depending on the fiber and resin type. Current finishing processes for composites are limited, and compatibility with existing processes such as E-coat is poorly understood. The cataphoretic deposition phase of the e-coating process, for example, can approach temperatures of 440ºF, close to the melting temperature of many thermoplastic resins such as polyamides and polyesters, thereby potentially degrading finished part material properties.

Existing painting and priming shop processes designed for metals will require modification and greater flexibility to accommodate carbon fiber composites while maintaining high production output capability. Limiting peak temperature during the painting process, for example, may not compromise production speed or finish quality and may avail designers a broader array of resin choices.

Potential enablers of cost-effective finishing of carbon fiber composites in the automotive industry include development of primer-in-mold (such as the process used for the body panels of the Tesla Roadster) and possibly paint-in-mold techniques that effectively replace certain aspects of the existing finishing process.

Tesla, Chaudhari et al, Fraunhofer

Autocomposites Project Overview & FAQ

Automotive Carbon Fiber Industry Context

Challenges to Widespread Implementation

Manufacturing Innovation

Design & Analysis Enhancement

Lifecycle Considerations

Approach to Overcome Challenges

3. Designing for performance and cost-effective producibility

Summary

As detailed in the previous section, "Enhancing Part Manufacturing," a key enabling element of cost-effective manufacture of carbon fiber composites is enhancing the means of production. But there is also a design component to this challenge: fully capturing the unparalleled material properties and parts consolidation potential of carbon fiber composite will require that the design-manufacturing interface be particularly well-integrated at the institutional level.

This will require that industry tooling capabilities be effectively communicated to OEM and Tier 1 manufacturing engineers and designers to ensure they are able to take full advantage of tooling capabilities in designing new means of production. Carbon fiber composite material standards and specifications must also be introduced in such a way that OEMs can seamlessly include the full array of material types in their portfolio of materials (or bill of materials [BOM]).

Design for manufacturability & assembly

Composite part designers can help reduce manufacturing cycle time and cost if they have in-depth familiarity with existing and rapidly-evolving tooling capabilities and manufacturing processes by which their designs can be fabricated. While the design-manufacturing dynamic already exists at the OEM and Tier 1 level, myriad composite part manufacturing pathways, together with assembly challenges, introduce significant additional complexity to the part development process for composites, thus requiring special attention to the structure, expertise, and interrelationship of the design, analysis and manufacturing functions.

Designing anisotropically

Practical considerations associated with manufacturability must nevertheless be balanced with knowledge and utilization of the anisotropic advantages of carbon fiber composites. Understanding the load paths of a part can help designers and structural analysts determine where costly carbon fiber material is needed, how the layup can be configured and oriented to drive maximum structural advantage, and where cheaper materials can be substituted. Tooling designers in dialogue with part designers can push existing tooling capabillities to reduce the limitations imposed on designers by manufacturability requirements. Manufacturing engineers can also develop new manufacturing processes to help expand design freedom. A healthy, ongoing push-pull relationship between part designers and tooling designers can help push the envelope on both fronts. While designers and tooling designers have always had a form of dialogue even with metal-based manufacturing processes, composites demand a more extensive and regular interaction.

Design for replacability and repairability

Knowledge of different adhesives and joining techniques can help enable easier downstream disassembly in case it is needed for repair or replacement.

Challenges

Several challenges hamper widespread adoption of automotive carbon fiber composite

Design & Analysis Enhancement

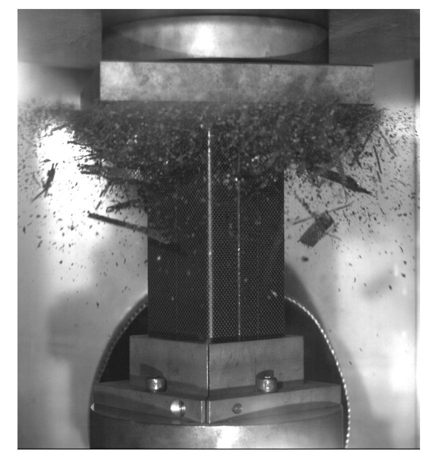
4. Enhancing the design & analysis toolset

Summary

Composites require an advanced set of design methods and computer aided engineering (CAE) tools to fully take advantage of their anisotropic and fragmentary properties. Material specifications and standards applicable to the automotive industry will be required to enable streamlined development and manufacturing practices and replicability of successes within the industry.

CAE tools can also play a critical role in identifying and advancing improvements to manufacturing processes by "virtually manufacturing" parts to ensure they achieve high cycle time and can be seamlessly integrated within existing vehicle production lines.

Crash Energy Absorption



The U.S. DOT has indicated that the crash energy absorption potential of carbon fiber composite is at least 4 times greater than that of steel, while a 2002 Daimler study found a 12x advantage of carbon fiber composite over steel (8x over aluminum), with thermoplastic resins showing the greatest potential. That there is an advantage over metals is clear, but the wide range of quoted values is symptomatic of the generally poor understanding of crash behavior of composite materials (along with the variety of potential material configurations). While metal structures absorb energy through relatively well-understood plastic deformation (with most crash structures designed to fold up like an accordion), the primary mechanism of energy absorption (in addition to standard plastic deformation) in composites is through material fragmentation (right). The level of fragmentation, corresponding to the fineness of debris created, determines the level of energy absorption. The extent to which designers can cost-effectively harness this mechanism (and avoid overdesign) in crash-critical components will be largely determined by the ability of CAE tools to accurately model it for various material configurations, from multi-ply unidirectional stackups to randomly-oriented chopped fiber and multiaxial weave systems.

Structural Validation & Optimization

Predictive modeling CAE tools with the ability to accurately analyze and optimize composite structures are critical to ensuring structural integrity and to ensuring that the full weight-saving potential of composite structures is captured. Approaches such as topology optimization, which uses an iterative process to determine the optimal placement (along load paths) of material within a given design space, along with advanced size & shape optimization, which determines the optimal configuration, orientation and ply order of ply stackups for composites, can play an important role in economizing use of material while deriving maximum benefit from it.

Virtual Manufacturing

Designers and structural analysts aren't the only ones who can benefit from advanced simulation tools. Modeling resin flow rheology in a new manufacturing process, for example, can help manufacturing engineers determine whether the latest process designs can meet the cycle time requirements of the industry. This can help reduce prototyping costs and speed the innovation process with respect to manufacturing and tooling.

Material qualification and specifications

The aerospace industry has developed an extensive set of material specifications and standards that help them certify structures and ensure predictable quality control and optimal processing allowables. However, only a few specific resin-fiber combinations, almost all of them based on epoxy prepreg, have been developed. The automotive industry is likely to be much more varied in its application of carbon fiber, with different grades of the fiber itself along with various uses of resin. Standards for all these combinations, along with processing allowables for the manufacturing processes in which they are used, will help ensure that designers avoid defaulting to overdesign due to uncertainty and that they have maximum freedom to tailor different grades of fiber, with different costs and material properties, to meet varying performance requirements, thereby helping to minimize manufacturing cost. For example, specifications might be developed that offer three grades of stiffness: cosmetic (i.e. mirror housings, 14-20 Msi), semi-structural (i.e. body panels, 20-25 Msi), and structural (i.e. engine cradle, 25-32 Msi). Part of optimization algorithms for automated CAE processes such as size & shape optimization could include these different grades among its optimization variables.

In addition to structural requirements relating to strength and stiffness, carbon fiber composite implementation will entail esablishing additional standards that address other material characteristics such as paintability, temperature resistance (heat deflection temperature, glass transition temperature, continuous use temperature, cold temperature performance), impact resistance, and corrosion resistance.

Due to the expense associated with esablishing material standards (and the commensurate competitive advantage associated with them), OEMs may initially be unwilling to share them and make them widely applicable; however, there may be mutual advantage to publishing such results so that supply chain innovators can work to cost-effectively meet OEM standards.

From a design standpoint, because material additives can significantly alter characteristics such as strength, toughness, and ductility, choices about additives are best made early to tailor materials to application needs.

Testing standards

Due to the many uncertainties surrounding the structural behavior of carbon fiber composites, physical testing will continue to play an important role for parts as they approach implementation. Of particular interest for carbon fiber composites are high strain rate testing to understand crash behavior and fatigue testing to understand long-term durability. While it is often said that carbon fiber is completely fatigue resistant, microcracks can nevertheless emerge and propagate within the resin matrix, thus creating stress concentrations that over time can lead to substantial damage. The many combinations of resin/fiber and material specifiactions can quickly lead to prohibitively costly testing regimes unless testing is carried out for a predetermined material type.

DOE Vehicle Technologies Program, Rehkopf 2012, ORNL

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5a. Carbon Fiber Composite Damage Detection and Repair Processes

Widespread automotive application of carbon fiber composites will require that cost-effective repair techniques be further developed so that replacement is not the only option. Insurance companies bear the cost of most damage to vehicles. Higher insurance costs for vehicles with carbon fiber composite parts could represent a downstream barrier to adoption if repair is not adequately addressed. Developing non-destrictive means of detecting damage will be integral to providing insurance companies with reliable means of assessing damage, mitigating risk of further structural failure, and avoiding assessing cost premiums to end-users. Warranties could be similarly affected if repair techniques are not credibly established for mainstream vehicles. Unlike malleable and ductile metals, carbon fiber composite exhibits brittle failure modes and often needs to be replaced entirely. The aviation industry was similarly challenged by damage detection. The 787 program nearly implemented a system known as structural health management whereby a grid of wires would be embedded in the composite matrix to detect breakage in oft-impacted areas such as the body near the baggage loading doors. In the end, the cost of such systems often outweighs the operating cost premium associated with a “when in doubt, replace it” policy.

Cricital enablers of cost-effective repair of carbon fiber composites in the automotive industry include development of accurate damage detection techniques; establishment of a knowledge base regarding repair techniques via facilities and certification processes to train and educate those in the field; certified repair shops; and sufficient communication and standardization of techniques to the insurance companies and warranty industry to avoid insurance cost premiums to the end user.

Particularly as the industry evolves from implementation of individual parts to full monocoque body-in-white construction with carbon fiber composites, repair techniques will play an increasingly important role.

Non Destructive Evaluation (NDE)

Most of the established means of detecting manufacturing and damage-induced defects for metals will not work reliably for composites. Among the techniques in use and under investigation are radiography, acoustics, ultrasonics, and eddy current. Even when some of these techniques are able to detect the *presence* of damage, they indicate little information about the *characteristics* of the damage.

Detection

Technologies assisting with the detection of cracks and verification of repairs include ultrasonic (the most common technique), thermography, computer aided tomography (CAT), shearography, resisitivity mapping, and laser vibrometry.

Vacuum curing repair

Vacuum curing involves creating a vacuum seal, usually with a vacuum bag, around a fissure or crack and infusing resin into the full thickness of the damaged area to re-bond separations. Most vacuum curing can be done at room temperature, but pre-heating is often performed to assist with evacuation of entrapped air. Aerospace material specification 3970 covers vacuum curing repair with prepreg.

Wet lay-up repair

Vacuum curing involves creating a vacuum seal, usually with a vacuum bag, around a fissure or crack and drawing resin into the full thickness of the damaged area to re-bond separations. Pre-heating is often performed to assist with evacuation of entrapped air. Aerospace material specification 3970 covers vacuum curing repair of prepreg.

Removability

Carbon fiber composite parts can often be attached with fasteners that enable removal, repair, and/or replacement. In the case of larger bonded substructures for which mechanical fasteners present their standard disadvantages (galvanic corrosion, weight, poor load distribution, abrasive damage), several adhesives are available that enable bond disengagement via heat application. On early versions of the Dodge Viper supercar, carbon fiber SMC fender supports were adhesively bonded to the steel spaceframe. Chrysler dealership mechanics could heat the part, remove it, and re-bond a new or repaired fender support in place.

Repair of Thermoplastics vs Thermosets

Due to the fact that they can be remelted, thermoplastics tend to be inherently more amenable to repair than thermosets. Thermoplastics tend to also be more ductile and damage-tolerant than thermosets and therefore less susceptile to cracks; however, if damage-affected areas can be fully populated with resin, much of the original integrity of the damaged part can often be obtained via repair even with thermosets.

5b. Recycling

Today's cars are among the most recycled consumer products. In particular, the steel in vehicles enjoys a recycling rate of nearly 100%[1]. Means of recycling carbon fiber composites must be developed to maintain the recyclability rates of today's cars. The vehicle recycling industry has stringent requirements around scrap availability, size reduction technologies, process parameters, and infrastructure for material collection.

Reclaiming and recycling processes

Carbon fiber composite recyclate can be broken down and recovered via several means. Thermoplastic-based carbon fiber composite is remeltable and thus amenable to fiber recovery via heat application. For thermosets that can't be melted, recovery processes include mechanical milling, shredding, and crushing that break down the composte into small pieces that can be sieved into powdered products (rich in resin) and fibrous products. The resulting products are typically used as filler for injection molding of lightweight parts.

Processes that more carefully separate the resin from the fiber, thereby preserving longer fiber lengths, are called fiber reclamation processes, including pyrolysis, fluidized bed oxidation, and chemical reclamation.

Pyrolysis leads to 0.25-1" fiber lengths with material properties about 80-90% of their original values. Milled recyclate can be pelletized or direct compounded for injection molding. Argonne National Lab made progress with a single-step pyrolytic process whose products were subsequently verified to be of similar diameter, density, morphology, and surface chemistry to those of virgin fibers. The ANL pyrolytic process is projected to remain economically viable so long as the original raw fiber has a value of $1.50 per pound.

Fluidized bed oxidation involves combusting polymer resin in oxygen-rich flow at elevated temperature (500°C). The resulting mixture is then cycloned to separate the fibers from resin fragments that are fully oxidized in an afterburner. The University of Nottingham has made advances with fluidized bed oxidation in recent years, producing nonwoven mats of recycled carbon fiber.

Chemical means can also be used to recover carbon fibers from their resin matrix, including catalytic solutions, benzyl alcohol, and supercritical fluids. Several of the processes have been tested at commercial and pilot scale. Adherent Technologies uses a chemical reclamation process to derive milled or chopped carbon fibers while recovering resin for use as fuel or chemical feedstock. Using water as the supercritical fluid was demonstrated at pilot scale by researchers at Florida State University, potentially enabling woven fabric to be recovered in its original form rather than as random mat, thereby improving performance of the recovered fiber.

In many cases recycle fibers exhibit comparable tensile modulus to their virgin counterparts, in some cases even showing improved modulus due to better mechanical interlocking resulting from modified surface morphology of the fibers.

Recycling Process	Advantages	Challenges
Melt & Recovery (Thermoplastic Resin Only)	Relatively simple process	Energy intensity, thoroughness of resin removal
Pyrolysis	Commercial scale implementation	Energy intensive
Chemical	Good preservation of material properties, potential to recover resin as chemical feedstock	currently require use of hazardous chemicals
Fluidized bed	Amenable to end-of-life and contaminated components	Causes material degradation
Supercritical fluid	Good preservation of material properties	New process: not commercial scale

1 When comparing the quantity of steel recycled from old vehicles versus the quantity of steel used in new vehicles. Steel Recycling Institute 2012
Rekhopf 2012.

Life-cycle

5. Ensuring life cycle robustness

Recycled carbon fiber implementation

Processes for implementing recycled carbon fiber into finished parts include injection molding, compression molding with sheet or bulk molding compound, and compression molding of non-woven forms.

Companies involved with using recycled carbon fiber include Rececyled Carbon Fibre Ltd, which manufactures filler and unidirectional fabric from carbon fiber recyclate, and Material Innovation Technologies, which creates preforms that can be molded or resin-infused.

Other processes under investigation include using chopped fiber in thermoplastic compounding, such as long fiber thermoplastic (LFT) molding and forming it into mats of nonwoven rolls of fiber for use in molding.

The resulting parts commonly have comparable tensile modulus but some degradation in strength that would make them applicable to stiffness-critical parts. With variable material specifications that would allow designers to choose among different materials (see previous section, "Enhancing the Design & Analysis Toolset," these materials could well make their way into the OEM and Tier 1 bill of materials.

Rekhopf 2012. Material Innovation Technologies

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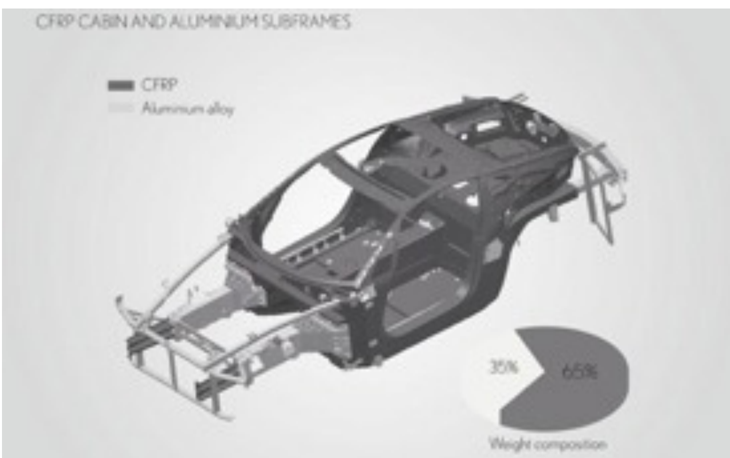
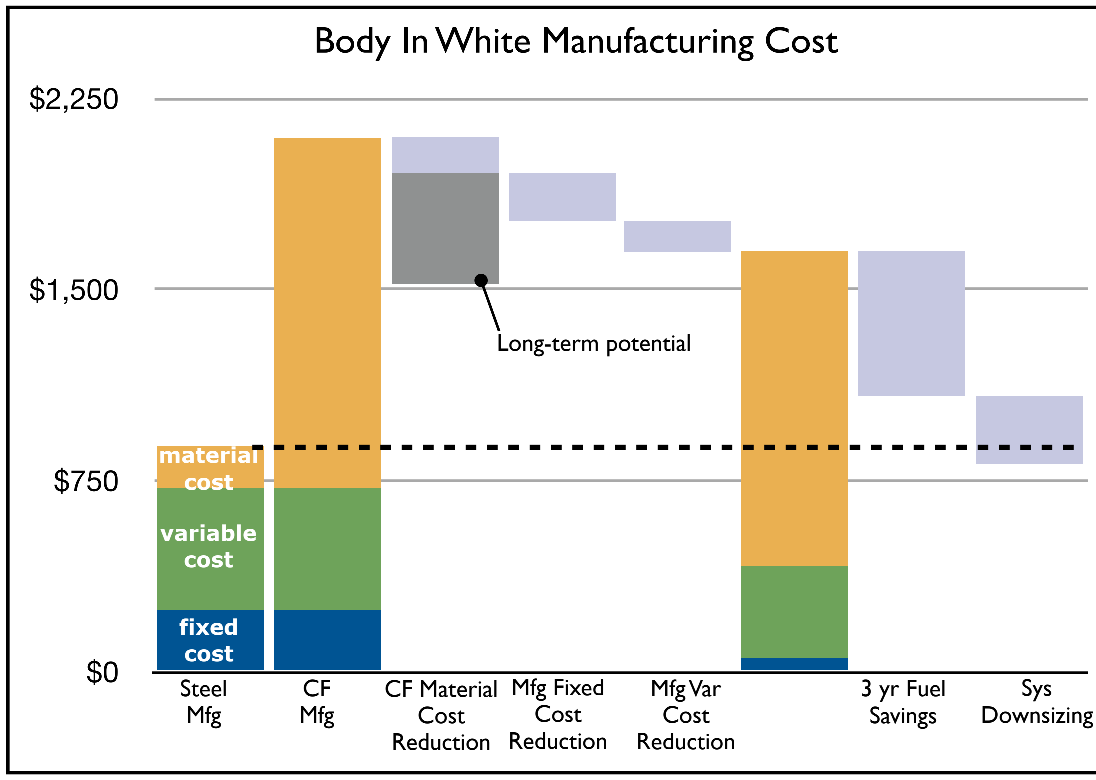
Approach

An initial substitution approach could pave the way to full implementation.

Where We're Going: The long-term vision

The vision of widespread, lightweight, cost-effective, fun-to-drive vehicles with MPGe well in excess of 100 within the next decade is one shared by many elements of the industry. A critical component of that vision is working toward the capability to design and produce very lightweight autobodies, made of advanced lightweight materials, at *scale*.

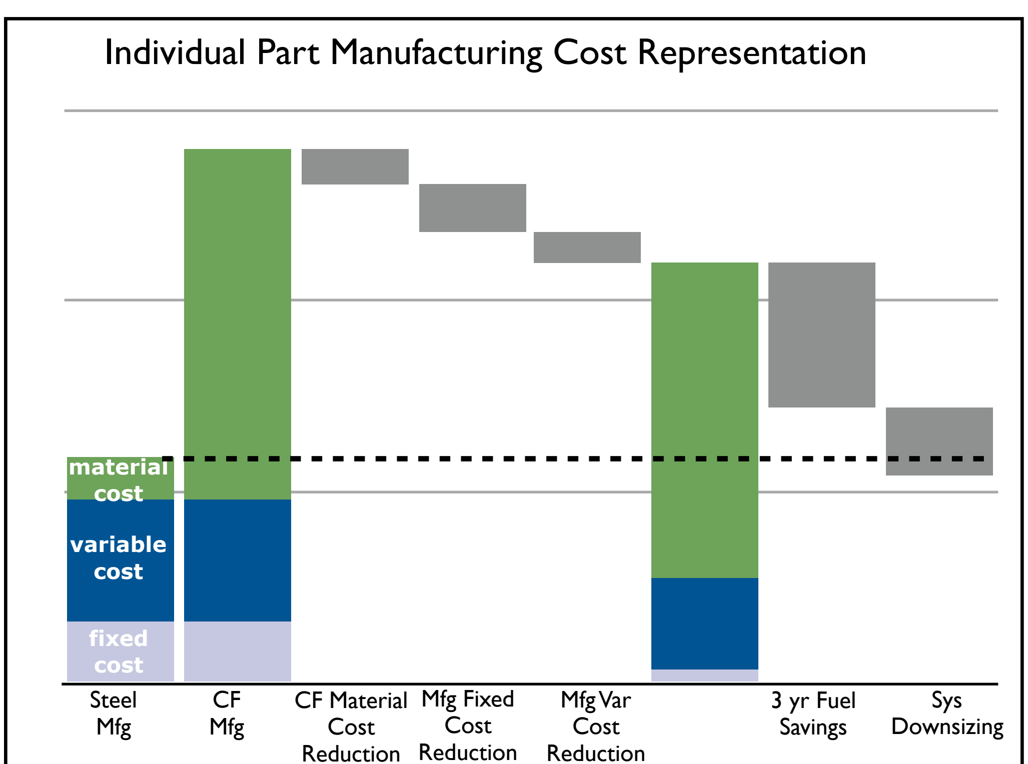




How we get there: A near-term approach

Adopting advanced autobodies made of carbon fiber composite and other advanced materials will entail substantial capital investment and disruption to the design process, product lifecycle, supply chain, assembly line, knowledge base, and manufacturing technology. Transitional steps will be required and the path is not yet clear.

Substitution to Transformation



Implementing individual carbon fiber composite parts on existing vehicle models could play a key role in enabling a stepwise approach toward the long-term vision of advanced material autobodies. Several niche applications of carbon fiber composite already exist, but most are not "scale-friendly" and they are not implemented within the context of a long term plan and vision.

Careful downselection of part candidates according to criteria that will enable speed and scale in the carbon fiber composites supply chain can reduce costs and pave the way for future parts, leading ultimately to full body in white capability.

Different stages of implementation can be planned out in advance by defining implementation "tiers."

Toyota, Truth About Cars

Approach

Carefully developed criteria can ensure initiation of a viable path to scale.

Part downselection criteria

Criteria	Notes
Weight reduction potential	Noticable to customer, e.g. shaved time off 1/4 mile time or increased MPG
Drives high production volume of raw material	Sufficient to build cost-reducing scale into the material supply chain
Below the skin	Avoids Class A finish requirement, which will become critical at later stages
Drives manufacturing innovation	Harnesses advances in manufacturing processes while offering opportunity to further advance them
Structural: Stiffness	Maximum weight savings will result from parts with high stiffness or strength requirements
Structural: Fatigue Loading	CF's fatigue resistance will lend durability and further weight saving benefit for fatigue-loaded parts
Drives design & analysis enhancement	Harnesses advances in CAE while offering opportunity to further advance it
Repairable or easily replacable	Assembled and attached to ensure easy removal
Recyclability	Will be more important at later stages, but select resin types and fiber forms amenable to recycle if possible
Drives establishment of material specs & standards	Utilizes a manufacturing process, fiber grade, and resin-fiber system with high applicability to future parts
Replaces part with high cycle time and/or cost	Lowers the bar for cost parity
Replaces multi-part assembly	Enables part consolidation
Amenable to multi-model implementation	Retrofittable in after-market or easily adaptable to other models
Safety	Safety may be a "dodgeable" challenge for initial implementation
Low Application Complexity	Avoids extensive testing and validation requirements for initial implementation
Corrosion benefit	CF can be more corrosion resistant than metals (although metal-CF interface should avoid galvanic corrosion and accommodate CTE mismatch)
Attachment: bolt on vs. integrated weldment	Bolt-on applications may avoid adhesive challenges for initial implementation

Approach

Tiered implementation phases can prioritize and map the steps to full implementation.

Blue: Significant Safety Requirements
Red: Finish Requirements (Above the Skin)

Near Term Parts	Mid Term Parts	Long Term Parts
Engine Mount/Cradle*	Corner module	Front End Carrier
Rear twist/suspension beam*	Front rail	Underbody Panels
Seats*	Torsion bar/stabilizer	Bumper Beam Carrier
Floor Panel/Floor Pan*	K-Frame	Door Sill Panel
Intrusion/Impact Beams*	Instrument Panel Carrier	Hood
Steering column carrier*	A/B/C pillar	Roof
Driveshaft**	Front end panel	Roof rails
Transmission Cradle**	Control arms	Sills
Transmission Tunnel**	Stabilizer bars	Crush rails
Door Inner**	Suspension Springs	Torque boxes
Hood Inner**	Crashbox	Structural rear quarter panels
Wheelhouse Inners**	Decklids	Cross car beam integrated with HVAC duct
Bumper Beam**	Door outers	Fenders
Battery Carrier	Suspension linkage	
Underbody Panels	Hatchback	
Trunk lid inner	Wheels**	
Front firewall		

A challenge-by-challenge tactical approach can help kickstart the path to scale.

Method:

Manufacturing Innovation: Reducing Raw Material Cost

Explore government or consortium-scale purchasing roles to help ensure a stable market, reduce investment risk and establish a multi-year, predictable raw material cost basis.

Establish industry specifications and standards to accommodate the wide range of required stiffness and strength in different automotive parts.

Identify research and development funding opportunities in the realm of raw material precursor and feedstock alternatives and advanced processes.

Identify and share means of mixing lower-grade or cheaper (i.e. glass) fiber to utilize carbon fiber only where its strength and stiffness is needed.

Manufacturing Innovation: Enhancing Part Manufacturing

Identify and understand cycle-time-related barriers to manufacturing with composites for mid-to-high vehicle volumes. Identify process innovations at the tooling level (individual parts) and the plant level (assembly & interfaces) that improve cycle time through collaborative teaming among automakers, national labs, academia, and process tool manufacturers & designers. Recommend measures to accelerate and incentivize adoption of cycle-time-related process improvements.

Identify challenging part families and shapes. Pursue technical solutions aimed at improving the supply chain capability to produce complex parts through collaborative innovation among automakers, Tier 1 suppliers, national labs (i.e. ORNL, ANL), academia, and process tool manufacturers & designers. Prioritize specific high-complexity part challenges and solutions. Recommend measures to accelerate technical solutions associated with high-complexity parts.

Identify and address tooling integration challenges and potential production process bottlenecks at the whole-plant level. Team with plant designers from the automotive and other relevant industries to minimize plant footprint, optimize material flows and nodes of material intersection, and pursue lean manufacturing practices.

Pursue technical solutions aimed at improving the supply chain capability to produce complex parts through collaborative innovation among automakers, Tier 1 suppliers, national labs, academia, and process tool manufacturers & designers.

Prioritize specific high-impact parts and associated challenges and solutions.

Design & Analysis Enhancement: Designing for Performance and Cost-Effective Producibility

Establish means of constant communication between tooling manufacturers and designers.

Recommend and identify best practices regarding provision of a fully integrated interface between manufacturing engineers and design engineers such as centralized knowledge sharing and integrated teams.

Ensure that carbon fiber composite material standards and specifications are introduced in such a way that OEMs can seamlessly include them in their portfolio of materials (or bill of materials [BOM]) for designing mainstream vehicles.

Approach

A challenge-by-challenge tactical approach can help kickstart the path to scale.

Method:

Design & Analysis Enhancement: Enhancing the Design & Analysis Toolset

Team with software providers and academia to identify means of enhancing "virtual manufacturing" software capabilities and best practices.

Identify challenging part examples and establish a central forum for sharing, testing, and validating virtual manufacturing models. Understand current safety validation tools, techniques, and challenges.

Team with software providers and academia to identify means of enhancing crash modeling software capabilities and best practices.

Work with existing collaborative frameworks such as the ACC to prioritize critical parts and challenges associated with crash safety and to strengthen means through which academia, software providers, automakers, and Tier 1 suppliers can collectively increase crash modeling software capabilities through prototype testing to validate model predictions.

Investigate means of providing raw material and resin in forms and grades specifically geared toward automotive applications.

Establish material specs and standards appropriate to automotive applications.

Establish an array of choices for material specs and standards to allow designers more freedom and to enable optimization software to optimally place and orient different grades of fiber as required.

Lifecycle: Ensuring recylability & repairability

Identify and prioritize promising recycling technologies. Understand cost, scale, and technology maturity tradeoffs. Identify existing recycling capacity and key players. Identify potential downstream sources and means of incorporating recycled carbon fiber in to existing manufacturing processes.

Ensure replacable parts by exploring different means of integration and attachment.

Overarching Approach:

Path to Scale

Identify promising individual composite part candidates that could be substituted for existing parts on existing models in order to drive scale and capability (and thus reduce cost) in the raw material supply chain, particularly for fiber grades appropriate to automotive applications. Build a roadmap to illustrate intermediate steps leading to full composite bodies-in-white. Understand and accommodate the means by which materials are typically selected for both existing and emerging products. Develop detailed, part-level business cases to illustrate the viability and/or gaps remaining to implement individual carbon fiber composite parts.

Develop a coordinated collaboration framework and plan that illustrates the role to be played and the benefit to be gained by each supply chain participant in a transition to large-scale adoption of composite parts. Understand and accommodate part specifications and requirements for parts supplied to OEMs by Tier 1 suppliers and for raw material provided from fiber manufacturers to Tier 1 suppliers. Explore means of enabling several stakeholders, via consortium, joint venture, or other teaming method, to enter into a risk-sharing investment aimed at enhancing the manufacturing capacity of the composites supply chain.

See the Workshop Overview Document for more detail on the workshop approach.