HEAVY VEHICLE MASS REDUCTION UTILIZING POLYMER COMPOSITES

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Abstract

Fiber reinforced polymers (FRPs) are promising materials for reducing vehicle mass, thereby improving energy efficiency and US energy security. Presently, the cost of using FRPs, especially with carbon fiber reinforcement, is quite high in comparison to conventional materials, and the lack of market incentives prevents their widespread use in passenger automotive structures. Furthermore, the material demand from even a small passenger automotive carbon fiber reinforcement application would overwhelm the carbon fiber supply chain. The Class 8 truck market offers modest financial incentives for vehicle mass reduction in some sectors, and vehicle build rates are low enough that the composites industry can satisfy demand without making step changes in capacity.

This suggests that a rational strategy for realizing the energy efficiency benefits of low mass composite materials in the transportation market is to develop and initially demonstrate new technology in the commercial vehicle market, with migration into the passenger automotive market as the technology matures. The US Department of Energy's (DOE's) FreedomCAR and Vehicle Technologies Office is therefore funding a significant research and development effort focused on heavy truck applications.

Background

Highway transportation in the U.S. consumes over half of the nation's oil demand and depends almost exclusively on petroleum fuels. U.S. economic prosperity is closely linked to petroleum fuels. Today roughly half of US petroleum demand is imported, and this poses significant risk to US national security and economic prosperity. Fuel demand for surface transportation is expected to continue increasing, as shown in Figure 1. Therefore the US Department of Energy funds work aimed at improving the energy efficiency of the nation's highway vehicle fleet. One of the DOE thrusts is dramatically reducing vehicle mass, which in turn reduces vehicle fuel demand. The principal approach to vehicle mass reduction involves the development and use of materials with high specific stiffness or strength, including high strength steels, advanced light metals, and fiber reinforced polymers.

Since the early 1990's, DOE and its laboratories have worked closely with automotive OEM's to develop and implement fiber reinforced polymer composite materials technology in automotive platforms. The work has been principally focused on affordable, competent materials; robust processing methods with short cycle times; joining; and energy management (crashworthiness). This effort has produced noteworthy achievements such as the development of a pickup truck box that could be manufactured in a four-minute cycle time, and which became available as an option on some Chevrolet light trucks.

Reinforcement material selection is very important. Glass and carbon fibers are the two most likely

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candidates. Glass-reinforced polymer automotive structures can be up to 30% lighter than the steel analogs, and carbon fiber reinforced structures can be up to 60% lighter than the steel versions. Until the late 1990's, conventional wisdom held that automotive composites would be restricted to the use of glass fiber, because carbon fiber was simply too expensive. Recent, more rigorous analysis suggests that technological innovation combined with value chain management and price-volume market effects could make carbon fiber reinforcement a viable automotive material. Therefore, DOE is now funding a major carbon fiber research and development program focused on making carbon fiber affordable to the automotive market.

Composites in Class 8 Trucks

Market Considerations

While it is widely accepted that reducing vehicle mass is a desirable goal, there are many barriers to realizing mass reduction in passenger automobiles. Technical barriers include crashworthiness, durability, robust manufacturing and joining technologies, design tools, and availability and quality of design data. Market barriers include material cost, materials manufacturing capacity, and the lack of an active market driver for mass reduction in passenger automobiles.

While many of these barriers are also relevant to the Class 8 truck market, there are marked differences, especially in market barriers. For example, about 30% - 50% of Class 8 tractor-trailers operate at the maximum allowable (usually defined by regulation) gross vehicle weight[1]. Reducing the tare weight of these vehicles will increase their payload and revenue capacities. The bulk haul sector, comprising 15% - 20% of the Class 8 truck market, is especially mass sensitive, with some customers willing to pay $5 premium in the truck purchase price for every added pound of payload capacity, and many customers willing to pay a $2/pound premium. These premiums offer the opportunity to use more costly materials to achieve tare weight reduction. Another advantage is that material volumes that will be required to serve the Class 8 truck market allow a more rational expansion of manufacturing capacity. A significant passenger automotive application requiring carbon fiber reinforcement would dramatically increase global demand and overwhelm the carbon fiber supply chain, which is currently a small industry. Typical US market demand for Class 8 trucks is about 200,000 units per year, so the required material volumes are modest and could be supplied if carbon fiber manufacturing capacity expands at a rational rate. Tooling for manufacturing composite structures is well-matched to Class 8 truck production volumes in terms of tool cost, cycle time, and tool life. The Class 8 truck market also allows more rapid insertion of new materials due to:

- Crashworthiness: occupant protection regulations are less demanding in Class 8 trucks than in passenger vehicles.
- Custom manufacture: Class 8 trucks are highly customized, so new component designs can be inserted within a few months after prove-out instead of waiting for the model changeover and associated retooling that occurs every few years in automotive manufacturing.
- Accelerated durability testing: materials durability testing typically consists of materials screening tests, laboratory structural testing and/or shake testing, and durability track testing, all of which can be completed in about six to eighteen months, depending on the consequences of failure.

Energy Considerations

DOE's principal motivation for investing in the development of polymer composites technology for commercial vehicle applications is to reduce the nation's energy demands, especially for imported petroleum. As shown in Figure 1, petroleum demand attributable to commercial vehicles (Classes 2b - 8, > 8,500 pound GVW) is growing, and the growth in surface transportation petroleum demand since 1970 is almost entirely attributable to trucks. Class 8 trucks use more fuel than all other commercial vehicle classes combined, as shown in Figure 2.

To check the rising demand for fuel, DOE has established a goal to develop technologies that will enable a 10 mpg Class 8 truck[2]. Similarly, the 21st Century Truck Partnership (21CTP) has established a goal to double the Class 8 line haul truck fuel efficiency on a ton-mpg basis[1]. Toward achieving these goals, DOE and the American Trucking Association have both set goals to reduce tractor-trailer tare weight by 5,000 pounds[2,3], and 21CTP's goal is 15% - 20% tare weight reduction[1]. Figure 3 shows the weight allocation for a typical Class 8 tractor with 70" raised roof sleeper. Based on 27,000 pound typical tractor-trailer tare weight, and 80,000 pound typical allowable GVW, a 20% decrease in tare weight would improve productivity efficiency by 10% for weight-limited vehicles. Since under half of the fleet is mass-limited, net fleet effect would be about 2% - 5% improvement in efficiency[1].

This small improvement in fleet efficiency does not by itself compel significant government investment. There exist other, more compelling, opportunities for Class 8 truck efficiency gains, e.g., aerodynamics and engine efficiency. An integrated strategy that addresses all surface transportation, however, suggests that investing in heavy vehicle mass reduction is important. US petroleum demand is dominated by automobiles and light trucks, as shown in Figure 1. Mass reduction in these vehicles can have a large impact on their fuel efficiency. The DOE investment in polymer composites for heavy vehicles is part of a strategy to develop, introduce, and mature mass reduction technology on vehicles that award a cost premium for mass reduction then migrate the matured technology to platforms that demand cost parity. In the process, both heavy and light vehicles will be made better, new jobs will be created, and our nation's energy security will be enhanced.

Service Environment

Class 8 trucks operate in an exceedingly demanding service environment that raises its own unique set of barriers to new technology introduction. In its essence, the Class 8 truck is a revenue-producing tool that must be incredibly reliable and durable. The expected truck life is 1 - 1.5 million miles. Service calls entail both maintenance expense and lost revenue; one extra service call over the truck's life can negate the benefit of performance enhancements. The service environment covers the full range of ambient temperatures, pressures, and humidity on earth, plus fully loaded transit over very rough roads or in some cases off-road. Chemical exposures may include very aggressive cleaning agents.

Project Portfolio

DOE is funding or co-funding several projects focused on the development of polymer composites technology applicable to heavy vehicles. These include cost-shared projects with near-term commercialization goals, and enabling technology development projects that are conducted principally by the DOE laboratories.

Cost-Shared Commercialization Projects

There are presently six cost-shared projects with commercialization as major objectives. Four of these projects are cost-shared industry projects that were awarded via competitive solicitation. The competitive solicitation encouraged responses by industry teams, and required each industry team to include at least one Class 7 or 8 truck or trailer OEM or component supplier. A 50% overall industry cost share was required, with at least 20% industry cost share in every project year. Required component mass reduction was 30%, with 50% targeted. Carbon fiber intensive designs were preferred, so as to increase carbon fiber demand and begin "descending the price-volume curve". Teams had to demonstrate intent and plans to commercialize the product within five years of project commencement. Two of the selected projects address truck body structures, and two projects address chassis/frame he selected projects include Two cost-shared projects are Cooperative Research and Development Agreements (CRADAs) conducted by Pacific Northwest National Laboratory with industry partners.

Delphi Corporation and other partners are developing **Advanced Composite Cab Structures**. This $1.6M project employs oriented glass fiber in vinyl ester matrix, sandwich construction, and single-piece tooling to effect 14 kg vehicle mass reduction at installed cost parity with the incumbent component. Key technical challenges include the development of inexpensive tooling and fiber placement techniques, and resin infusion in large, 1.5 mm thick panels. The design concept appears to surmount those barriers while providing significant performance enhancements to the customer. Start of production is expected within two years. The component will initially be deployed on a low production volume truck, with intention to later migrate to a higher volume model. Initial designs with carbon fiber were found to be too expensive, hence this particular component is currently utilizing an all-glass design, with plans to incorporate carbon fiber for further mass reduction when carbon fiber pricing becomes attractive.

Volvo Trucks North America and Meridian Automotive Systems are developing a **Carbon Fiber SMC Hood System**. This $7.5M project aims to develop a Class 8 tractor hood system that is 20 - 30 kg lighter than the incumbent hood system. This will require the hood thickness to be reduced from about 3 mm thick to 1.5 mm - 2 mm thick. The project team contemplates the development of a sheet molding compound (SMC) with 100% carbon fiber reinforcement in polyester matrix. Major technical challenges include SMC materials development, in-mold flow, and Class A surface finish. Effort is presently focused on the development of a competent SMC material. Project completion and commercialization decisions are scheduled for early 2007. Economical carbon fiber SMC could have a very large impact, since approximately 70% of automotive composites are made from SMC[4], and manufactured parts could probably be "drop-in" replacements.

Delphi Corporation and partners are developing **Advanced Composites Structural Chassis Components.** This $2.6M project aims to develop three chassis/suspension components that deliver ~ 60 kg vehicle mass reduction. A carbon fiber intensive tie rod has been developed. It is currently being field tested, and the vendor is accepting advance orders. Tie rod development is described in detail by Witucki et. al[5]. Another component was initially designed for composites, then the composite design was adapted for aluminum. The prototype aluminum component, which is estimated to reduce vehicle mass by 25 kg and cost less than the incumbent part, has been manufactured and is undergoing testing. Finally, a massive steel component is being redesigned as a metal-composite hybrid component, with estimated mass reduction exceeding 30 kg based on the current design concept. Carbon fiber purchase cost and composites fabrication cost appear to be the major commercialization barriers on this project.

Delphi Corporation and multiple OEM partners are developing **Advanced Composite Support Structures**. This $6.0M project aims to develop chassis/frame components that deliver up to 125 kg vehicle mass reduction. Major technical challenges, in addition to materials and manufacturing cost, include numerical fatigue modeling and attachment technology. This project commenced recently, and is currently in the value engineering and analysis phase. OEM-specific component selection will occur within a year. Commercialization decisions and start of production are scheduled in 2007.

PACCAR, Inc and PNNL are partners (under a DOE CRADA) on a project that is focused on development of a lightweight hybrid material heavy truck door system. The **Hybrid Composite Materials for Weight Critical Structures** project is evaluating the application of hybrid carbon fiber/glass composites, along with lightweight metals for cab doors. Key project objectives are to reduce the door weight and cost compared to the current glass-reinforced SMC door, and to increase the stiffness of the door for improved structural performance and weather sealing. Three prototype doors are being developed by the partner team, and vehicle testing is scheduled in 2004.

Another CRADA between PNNL and Freightliner LLC is investigating selective carbon fiber reinforcement of large composite structures for truck cabs. The project, **Application of Carbon Fiber for Large Structural Components** is evaluating the use of hybrid glass/carbon fiber preforming methods using automated preform technology. Selective placement of carbon fiber in critical load-bearing locations is expected to reduce the cost and improve structural performance of large cab components. The project is also evaluating the use of Multiple Insert Tooling (MIT) for liquid molding of large Class A surface components. Contributing participants include carbon fiber supplier Toray USA and Reichhold Chemical is supplying modified resin systems for the project.

The work done to date on cost-shared,

commercialization projects has produced some very important lessons, as well as reinforcing some existing knowledge. A few important observations from this work include:

- The target is always moving. In some cases, incumbent part designs are being improved even as the composites design is under development. Improvements made with conventional materials often move the cost and/or technical target during the composites application development project.
- Allowable cost premiums are very dependent on market sector and the industry's economic state. Available cost premiums have shrunk along with the US economy and trucking industry revenues.
- The high purchase price of carbon fiber prevents its use in meaningful volumes. For several years, there has been general agreement that the commercial grade carbon fiber purchase price would have to be in the range of $6.60/kg ($3/lb) to $11/kg ($5/lb) before it could be economically viable in the automotive industry. These projects have consistently identified the critical carbon fiber price point, through rigorous analysis, to be ~ $9.90/kg ($4.50/lb).
- The ability to mold thin sections is critical to fully exploiting carbon fiber's properties and paying its price.

Direct Funded, Enabling Technology Projects

As noted above, carbon fiber offers compelling technical benefits but is currently too expensive for use in most commercial vehicle and automotive structures. DOE is funding an R&D program focused on reducing carbon fiber's cost. Most commercial grade fiber is made from polyacrylonitrile (PAN) precursor by thermal pyrolysis as shown schematically in Figure 4. The major cost elements are the precursor fiber, oxidation/stabilization (denoted thermoset in Figure 4), and carbonization. Commercial grade fiber receives little or no graphitization. DOE is funding projects focused on reducing the cost of PAN precursor, developing inexpensive alternative precursors, and developing plasma-based techniques for oxidizing and carbonizing the precursor. PAN treatments that allow use of a less expensive grade of precursor have been developed, and could be implemented within about two years. Lignin-based precursor is being developed, and satisfactory chemical composition and fiber spinning have been demonstrated in small quantities. Plasma-based carbonization has been operated at line speeds exceeding conventional line speed, but only with a single-tow line. It is now being upgraded to higher tow count. Plasma-based oxidation, which receives heavy vehicle program funding, has been demonstrated to be technically feasible. Both evacuated and atmospheric pressure plasma are being investigated, with evacuated plasma providing simpler control of reactive species and atmospheric plasma simplifying the removal of heat generated in the fiber during oxidation/stabilization. Oxidation/stabilization rates have received little attention to date, but will be a critical part of future investigations, since oxidation is the rate-limiting step in carbon fiber conversion.

The lack of economical, robust attachment techniques is a major barrier to the successful application of polymer composites in chassis, frame, and support structures. ORNL and PNNL recently began working together to address this problem. The project team intends to develop and validate joint designs that satisfy Class 8 truck structural requirements. Deliverables will include design data and design guidance documents. The project is coordinated with Delphi's support structures project, which will have immediate access to the design data and will perform durability track testing of a selected joint design. The project is described in greater detail by Klett and Herling[6].

Class 8 truck OEM's and suppliers consistently identify part production tooling cost and lead time as major challenges, because of the large part sizes and low production volumes. ORNL and PNNL are therefore evaluating tooling technology status, needs, and emerging technologies. The evaluation will address materials of construction using metals, fiber-reinforced polymers, and unreinforced plastics, with emphasis on part sizes and production volumes typical of Class 8 truck manufacturing. Three regional workshops, located in the Seattle/Portland area, Detroit area, and an Atlantic coast state, will be conducted this year to solicit industry guidance. Recommendations will be submitted to DOE in 2004.

Summary

Mass reduction in passenger automobiles can have a large effect on the nation's fuel demand and energy security, but Class 8 trucks offer better market incentives for mass reduction. Therefore DOE is funding efforts to reduce truck mass, with plans to later migrate the technology into automotive platforms. Cost-shared commercialization projects should see a number of products implemented in Class 8 trucks within five years, with one product already on the market in limited quantities. Enabling technologies, including carbon fiber cost, attachment technology, and tooling, are being addressed at the DOE national laboratories. Implementation of laboratory solutions will require a longer time frame and are dependent upon industry acceptance and collaboration for commercialization.

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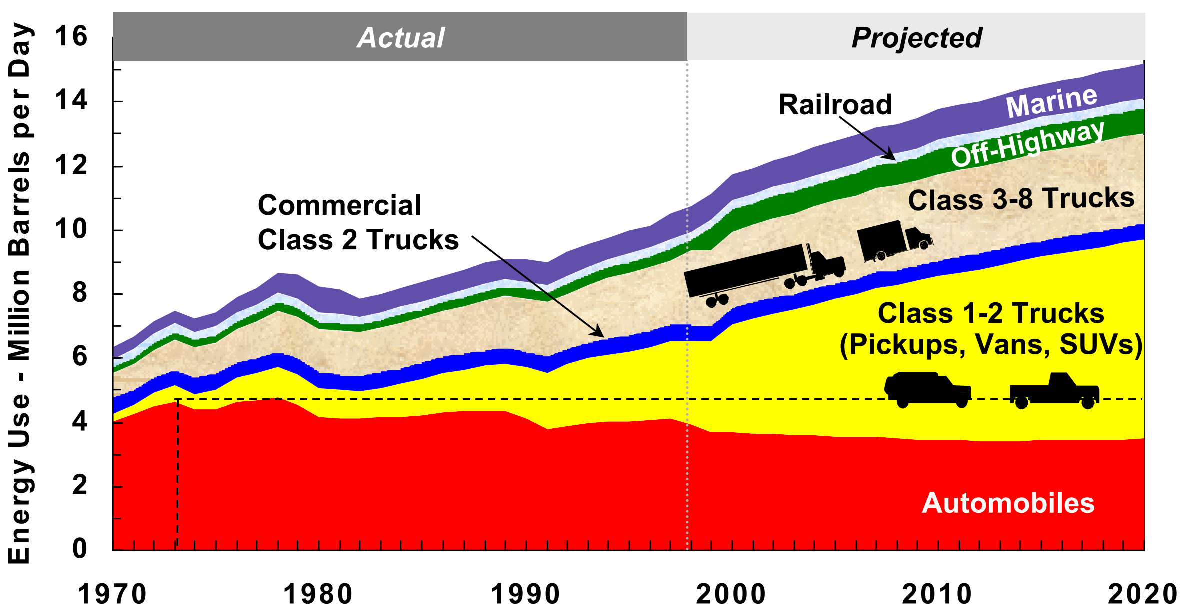
Figures



Sources: *EIA Annual Energy Outlook 2002*, DOE/EIA-0383(2000), December 2001
Transportation Energy Data Book: Edition 21, September 2001.

Figure 1: Growth of US surface transportation fuel consumption

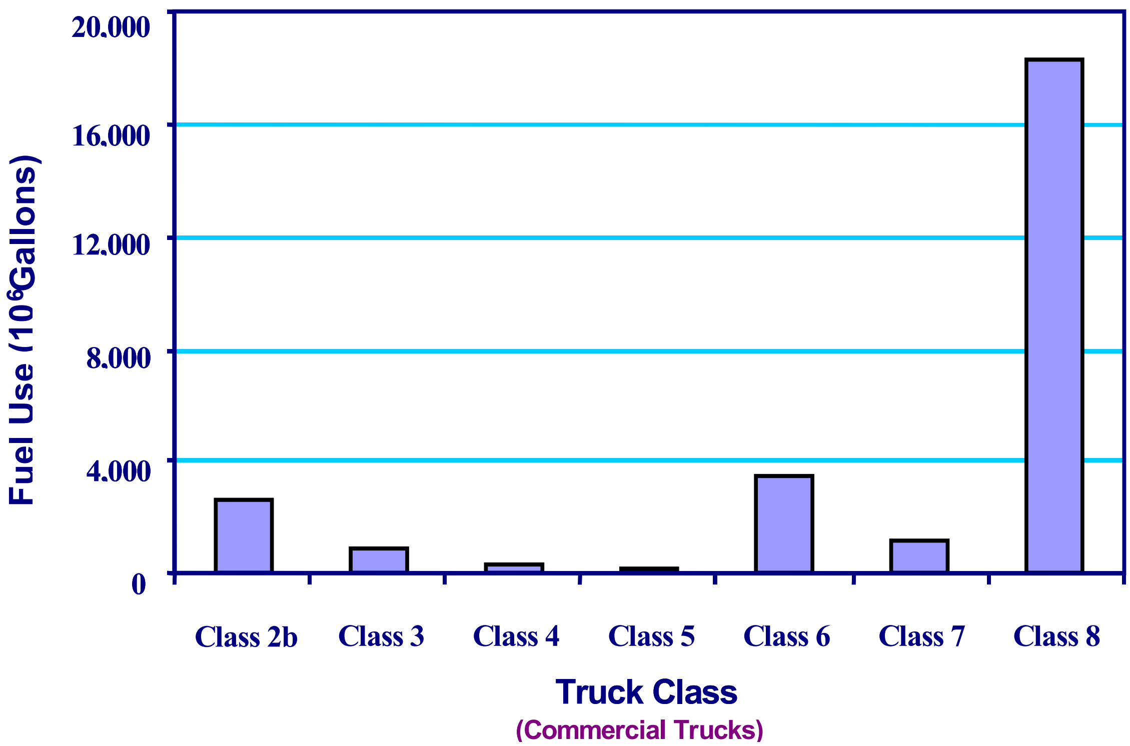


Figure 2. Fuel use by truck class

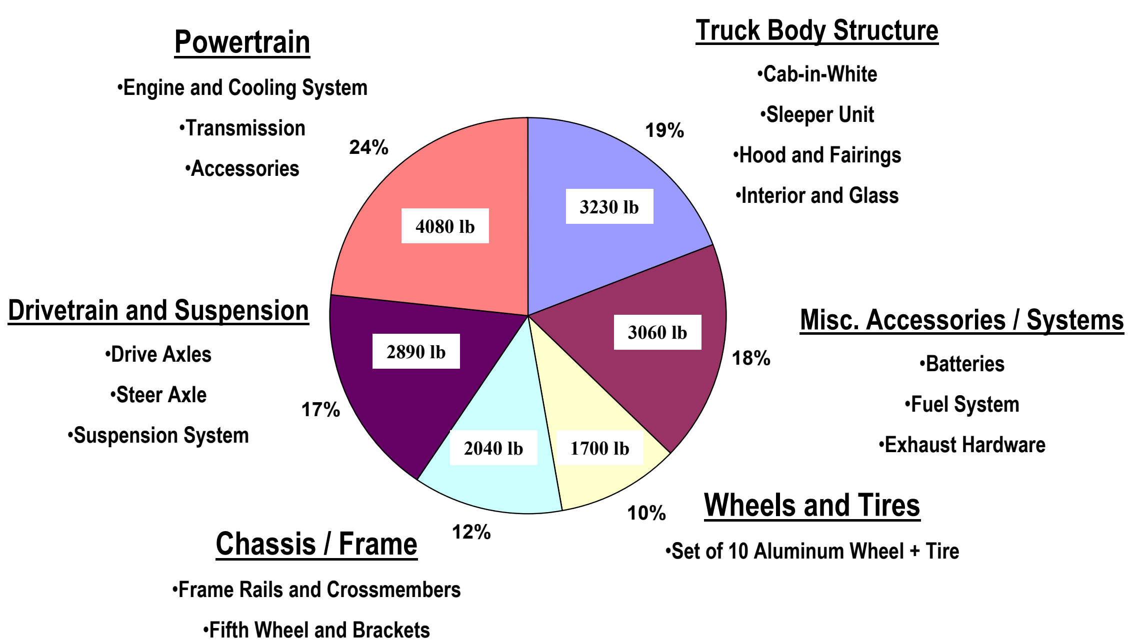


Figure 3. Weight allocation of Class 8 tractor with raised roof sleeper.

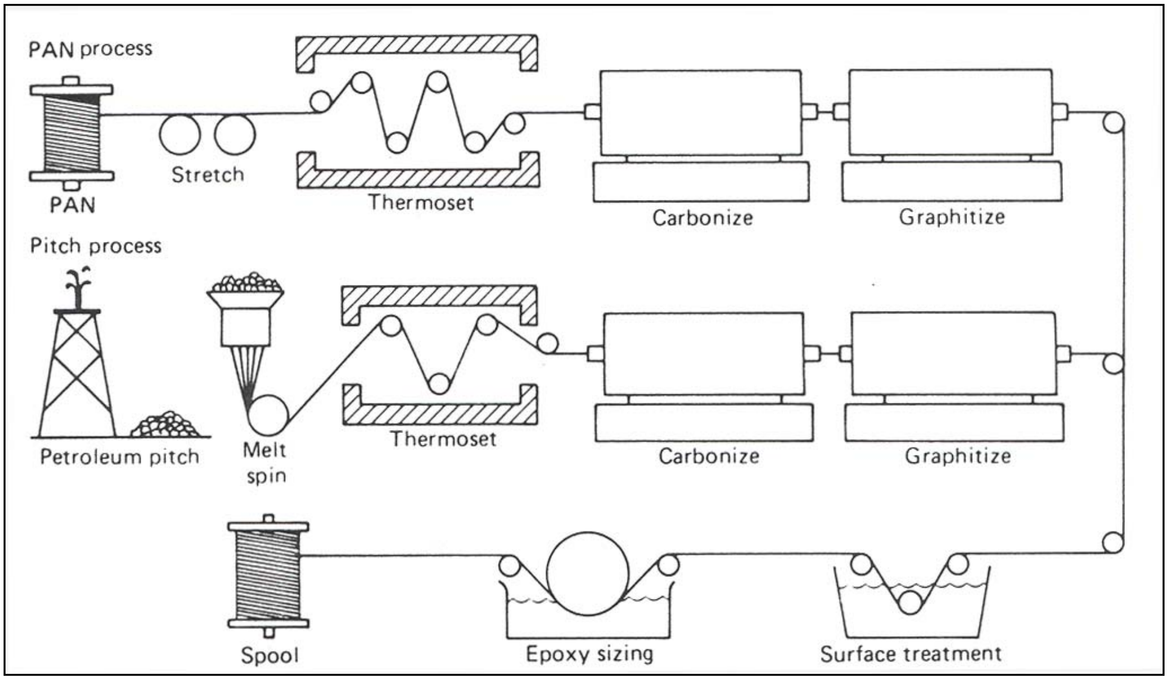


Figure 4. Carbon fiber manufacturing steps.

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