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DOE AUTOMOTIVE COMPOSITE MATERIALS RESEARCH: PRESENT AND FUTURE EFFORTS

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INTRODUCTION

Automobiles of the future will be forced to travel further on a tank of fuel while discharging lower levels of pollutants. Currently, the United States uses in excess of 16.4 million barrels of petroleum per day. Sixty-six percent of that petroleum is used in the transportation of people and goods. Automobiles currently account for just under two-thirds of the nation's gasoline consumption, and about one-third of the total United States energy usage. [1] By improving transportation related fuel efficiency, the United States can lessen the impact that emissions have on our environment and provide a cleaner environment for future generations.

In 1992, The Department of Energy's (DOE) Office of Transportation Materials completed a comprehensive program plan entitled, The Lightweight Materials (LWM) Multi-Year Program Plan, for the development of technologies aimed at reducing vehicle mass [2]. This plan was followed in 1997 by the more comprehensive Office of Advanced Automotive Technologies research and development plan titled, Energy Efficient Vehicles for a Cleaner Environment [3] which outlines the department's plans for developing more efficient vehicles during the next fifteen years. Both plans identify potential applications, technology needs, and R&D priorities. The goal of the Lightweight Materials Program is to develop materials and primary processing methods for the fabrication of lighter weight components which can be incorporated into automotive systems. These technologies are intended to reduce vehicle weight, increase fuel efficiency and decrease emissions. The Lightweight Materials program is jointly managed by the Department of Energy (DOE) and the United States Automotive Materials Partnership (USAMP). Composite materials program work is coordinated by cooperative research efforts between the DOE and the Automotive Composites Consortium (ACC). Current composite materials program focus areas address long term material durability, adhesive joining methodologies, high rate manufacturing methods, crash testing and modeling, non-destructive evaluation, low cost carbon fiber production and advanced production method development. A joint DOE/ACC roadmap for future technology development is currently being formulated.

PROGRAM BACKGROUND

A significant reduction in fuel consumption can only be achieved by one of three means: (1) improving engine and drivetrain efficiency; (2) reducing automotive component mass and thus vehicle weight; or (3) reducing the volume and thus weight of an automobile. Studies have shown that a 25% weight reduction in current United States vehicles would save 750,000 barrels of oil each day, reduce the yearly domestic fuel consumption by 13% and prevent 101 million tons of CO_2 from being emitted into our atmosphere each year [4]. If this body and chassis weight savings is coupled with a smaller engine that would achieve the same vehicle performance, then an additional 5% total fuel use reduction is achievable which would save a total of 900,000 barrels of oil each day and prevent 122 million tons of CO_2 from being released into the atmosphere annually. Reducing the mass of rapidly moving engine components, which must reverse momentum during engine operation, would provide an additional savings.

Not only does transportation technology affect the world environment but it also has a major impact on the economy of the United States. In 1991, the American automotive industry was responsible for 4% of the gross national product and directly accounted for 12.87 million jobs, according to economists at the University of Michigan [5]. The $200 billion automotive industry uses 23 million tons of material annually to produce about 12 million vehicles, while employing one out of seven American workers directly or in related industries. It also accounts for approximately $40 billion of our annual foreign trade deficit. [6] The future of the United States automobile industry is the economic future of America. Advanced transportation materials which result from advanced materials research have the potential to make the United States the leader in automotive technology and environmental responsibility.

Timely availability of new materials and their manufacturing processes is critical for the development and engineering of advanced light-duty vehicles. A primary need is for lighter weight materials with sufficient strength and stiffness to replace conventional materials (i.e., mild steel) for body, chassis, and powertrain applications. An equally important need is for materials with optimum performance at operating conditions to enable advanced propulsion systems. The Office of Advanced Automotive Technologies (OAAT) is addressing these needs by sponsoring development of materials and materials-processing technologies; validating these technologies through representative component prototyping; and developing adequate design data to ensure their beneficial application. The OAAT Advanced Automotive Materials Program is working with the automotive industry, through the U.S. Automotive Materials Partnership (USAMP), to facilitate the development, by 2004, of test-bed vehicles that are 40% lighter (50% for body and chassis) than current vehicles with comparable capabilities. This program directly supports the Partnership for a New Generation of Vehicles (PNGV) which exists to develop an 80 mpg (34.0 km/l) BTU equivalent vehicle by 2004. It also supports a longer term DOE goal of developing a 50% lighter (60% for body and chassis), 100mpg (42.5 km/l) BTU equivalent vehicle by 2011. [3]

One method of increasing automotive energy efficiency is through mass reduction of structural components by the incorporation of composite materials. Significant use of glass reinforced polymers as structural components could yield a 20-30% reduction in vehicle weight while the use of carbon fiber reinforced materials could yield a 40-60% reduction in mass. [7] Specific areas of research for lightweighting automotive components are listed below along with research needs for each of these categories [3]:

1. **Low Mass Metals** - Aluminum has a density that is 1/3 that of steel and could be used in both structural and engine applications. Magnesium and titanium have densities even lower than aluminum. The technical obstacles to be overcome include the development of high rate forming and casting methods, technologies for reducing the raw material costs, rapid and reliable methods of joining these materials to dissimilar materials and systems for sorting the post-consumer components for recycling.

2. **Polymer Composites** - Polymer based composites have densities that are 1/6 to 1/3 that of steel depending upon the fiber type, fiber loading and resin system chosen. The technical obstacles to be overcome are essentially the same as that for low mass metals, however, the technical details of overcoming those obstacles are quite different due to the differing inherent properties of the materials. Data on the long term use of these materials in an automotive environment needs to be developed as well as design and processing methodologies for taking advantage of the unique properties of this class of materials.

3. **Ceramic Materials** - These materials are lighter than steel and have excellent high temperature stability which makes them particularly attractive for use as engine components. Technologies for high volume manufacturing of these materials and data on long term use of these materials in an automotive environment need to be developed.

An 80 mpg BTU equivalent vehicle is currently possible with existing technology. It is, however, not economically feasible because the cost of the vehicle would be far in excess of what consumers are willing to pay. Research into lightweighting automobiles must focus on making the production of advanced automotive components using advanced materials economically feasible. This can be accomplished by coupling the advanced materials knowledge present in the federal laboratory system and the composites industry with the understanding of realistic, high volume manufacturing issues present in the domestic automotive companies and suppliers. By necessity, the research must have economic as well as technical and environmental goals and encompass the total life cycle from raw material production to post-consumer recycling.

COMPOSITES IN TRANSPORTATION

The commercial application of composites has an extensive history in the marine, aerospace and construction industries but has evolved relatively slowly in the automotive industry during the past 20 years [8,9]. Composite use in automobiles has historically been limited to secondary structures such as appearance panels and dash boards [10]. The major obstacles to automotive industry implementation of polymer based composites stem from a variety of factors including industry inexperience with these materials, undeveloped high production rate processes, the need for new joining techniques, lack of knowledge about material responses to automotive environments, lack of crash models, immature recycling technologies and a small supplier base. In addition to the limiting factors listed above, carbon fiber based composites are restricted in industry use due to the high current cost of carbon fiber in comparison to other potential vehicle structural materials. The greatest cost factors in carbon fiber production are the high cost of precursors and the high capital equipment investment required. [11]

The distribution of materials in the typical 1997 passenger car is shown in Table 1. [5] The total weight shown is comparable to the average weight of the PNGV baseline reference vehicles (1994 Ford Taurus, Chevrolet Lumina and Chrysler Concorde). This table shows some alternative materials and their potential weight savings. To achieve the PNGV weight reduction target of 40%, a significant portion of the steel and iron must be replaced with aluminum or composite materials.

TABLE 1

Distribution of Materials in a Typical Vehicle

Material	1997[a] weight lb (kg)	Alternative material	Potential weight savings lb (kg)
Regular steel sheet, tube, bar, and rod	1411 (641.4)	Sheet: Carbon fiber composite	890 (404.5)
		Sheet: aluminum	670 (304.5)
		Springs: titanium	20 (9.1)
High & medium strength steel	295.5 (134.3)	Carbon fiber composite	150 (68.2)
		Aluminum	130 (59.1)
Stainless steel	47.5 (21.6)	Titanium	20 (9.1)
Other steels	36.0 (16.4)	-	0
Iron	378 (171.8)	Cast aluminum	190 (86.4)
Plastic & plastic components	242 (110)	-	0
Aluminum	206 (93.6)	Magnesium	100 (45.5)
Copper and brass	46.5 (21.1)	Fiber optic cable	20 (9.1)
Powder metal parts	31 (14.1)	Metal matrix composite	10 (4.5)
Zinc die castings	14 (6.4)	-	0
Magnesium castings	6 (2.7)	-	0
Fluids, lubricants	197.5 (89.8)	Less fuel on board	85 (38.6)
Rubber	138.5 (63.0)	-	0
Glass	96.5 (43.9)	Plastic or thin glass	35 (15.9)
Other materials	102 (46.4)	-	0
TOTAL	3248 (1476)	Total savings/aluminum intensive	1270 (577)
		Total savings/composite intensive	1520 (691)

[a] Source: American Metal Market from industry reports.

The major goal of the LWM program is to develop and validate cost-effective lightweight materials technologies that could reduce vehicle weight without compromising vehicle cost, performance, safety or recyclability. The road map to achieving this goal is to develop and validate advanced materials technologies according to the following agenda. These goals are to be achieved by exhibiting performance, reliability and safety characteristics comparable to those of conventional materials while being competitive with the life-cycle costs of conventional materials. [3]

1. By 2000, enable a 25% reduction in the weight of body and chassis.
2. By 2004, enable a 50% weight reduction in body and chassis components and a 40% reduction in total vehicle weight, which leads to an 80 mpg (34.0 km/l) BTU equivalent vehicle.
3. By 2011, enable a 60% reduction in the weight of body and chassis components which leads to 100 mpg (42.5 km/l) BTU equivalent fuel economy.

TECHNICAL BARRIERS

To achieve the PNGV goal of 40% weight reduction by 2004 and the OAAT goal to achieve 100 mpg (42.5 km/l) BTU equivalent fuel economy by 2011, a systems approach is being taken. That approach is aimed at overcoming the technical obstacles, including cost, of using this class of advanced materials. Specific technical barriers [3] that are being addressed are:

1. Cost. Primary resin and fiber costs present the single greatest barrier to the use of composite materials in automotive applications. Carbon fiber precursors are too expensive and precursor processing methods are too slow and costly. With the exception of glass, other reinforcing fibers also tend to be too expensive. Resin systems are often low volume commodities with specialized uses and limited application development.

2. Manufacturability. Current methods for the high-volume production of automotive components from composite materials have not been adequately developed. Composite processing technologies need to be developed that yield the required component shape and properties in a cost-effective, rapid, repeatable and environmentally-conscious manner. Processing technologies must be compatible with automotive manufacturing plants and methodologies.

3. Design Data/Test Methodologies. Adequate design data, test methods, analytical tools and durability data do not exist for automotive grade composite materials that could be used in primary structural components.

4. Joining. Rapid, high volume joining technologies for composite and dissimilar material joints need to be developed. Fast, reliable methods to test joint and component integrity are also needed along with advanced design methodologies.

5. Recycling and Repair. Technologies for cost effective recycling and repair of composites do not exist and must be developed.

TECHNICAL APPROACH

Advanced technologies for primary fabrication, secondary processing, forming, joining and recycling are being developed. DOE is addressing these imperatives by developing materials and processing technologies, validating these technologies through fabrication and evaluating representative component test articles. DOE is also developing design data, models and methodologies to facilitate the application of composite materials. These technologies are validated by joint DOE/ACC focal projects which demonstrate program goals. Focal projects are centered on specific classes of materials using nonproprietary components. As technical barriers are removed through research validation, the technology is made available for industry to take in-house to perform proprietary, application specific research. The current focal project, near completion, demonstrates the cost effective production of a large, glass reinforced automotive structure at industry acceptable costs and production rates and at a 25% mass savings over steel structures. The next focal project will develop a carbon fiber based structure aimed at proving cost effective producability with a 50% mass reduction when compared to steel.

Lightweight materials research addresses the high priority barriers that will reduce life-cycle costs and the risk involved in introducing innovative materials [3]. The following areas of research are being pursued. Note that all areas of research affect cost.

1. Material Cost

Carbon Fiber. Carbon fiber is currently produced by controlled pyrolysis of precursors at volumes that are small compared with the needs of the automotive industry. Research is being pursued that seeks to use new classes of very low cost precursors and provide the tools for scaling up precursor volumes. Alternate energy absorption methods for processing of precursors into carbon fibers are also being pursued.

Resin Systems. Alternate resin systems are being investigated which includes the identification of currently available systems for composite fabrication and the alteration of current resin systems to meet industry needs. Advanced non-thermally processed systems are also being pursued.

2. Manufacturability

Preforming. High rate preforming techniques are being developed that use water slurry and dry spray-up methods to obtain chopped-fiber preforms with consistent fiber densities at the volumes required by industry. Continuous fiber preforming is also being pursued for thermoset systems and for use in thermoplastic sheet systems that can be thermally formed.

Processing. Technologies are being pursued for high volume production of both thermoplastic and thermoset materials. These technologies include but are not limited to high volume injection molding, injection compression molding, net-shape forming, themoplastic thermoforming, resin transfer molding, non-thermal curing methods, and automated material handling systems.

3. Design Data and Test Methodologies

Durability. Programs are being pursued to develop the necessary understanding and predictive capability to assess the effects of low-energy impacts, creep, fatigue, automotive fluids, temperature extremes and other influences to which materials will be subjected in an automotive environment. Predictive models are being developed that allow designers to account for the synergistic effects of environmental stressors.

Design Methodologies. Technologies are being pursued to develop design methodologies and use philosophies that take advantage of the positive properties of composite materials while minimizing the effects of their less desirable properties. These are being validated by joint DOE/ACC focal projects which develop production prototype test articles that represent automotive structures and subsystems.

Energy Management. Theoretical and computational models are being developed for predicting energy absorption and dissipation in automotive composites. These models will give designers the tools to minimize component weight while maximizing occupant safety.

4. Joining and Inspection

Joining. Technologies for joining composites to composites and to other materials are being developed. Current efforts concentrate on formulating, modeling, processing and testing of adhesive bonds. Significant work is being conducted to understand the synergistic effects of environmental stressors on adhesive joint integrity. Future efforts will concentrate on thermoplastic welding, thermoset reaction bonding, adhesive rapid cure technologies, bolting, and novel attachment technologies.

Non-Destructive Evaluation. Methods for evaluating bond integrity are being developed that are able to qualify and quantify bond strength. These methods are robust enough for a manufacturing facility, fast enough for a production line and reliable enough to ensure passenger safety. To date the best success has been gained by the application of laser shearography.

5. Recycling and Repair

Recycling. Methods are being pursued for separating glass and carbon fiber from thermoset and thermoplastic resin systems. Efforts are also underway to identify alternate uses for post-consumer automotive grade composites.

Repair of composites. Robust methods will be developed for rapidly and reliably repairing composite structures. The cost effectiveness of repair vs. replacement of components will be considered. The outcome of this evaluation will influence the joining technologies needed to incorporate composite materials.

GLASS REINFORCED COMPOSITE MATERIALS

In the early years of the program, significant emphasis was placed on developing composite processing, joining, energy management and design technologies using glass reinforced polymers. The first focal project to utilize these research efforts was a Ford Escort front-end structure designed for energy management. That focal project was successfully concluded meeting all technical objectives.

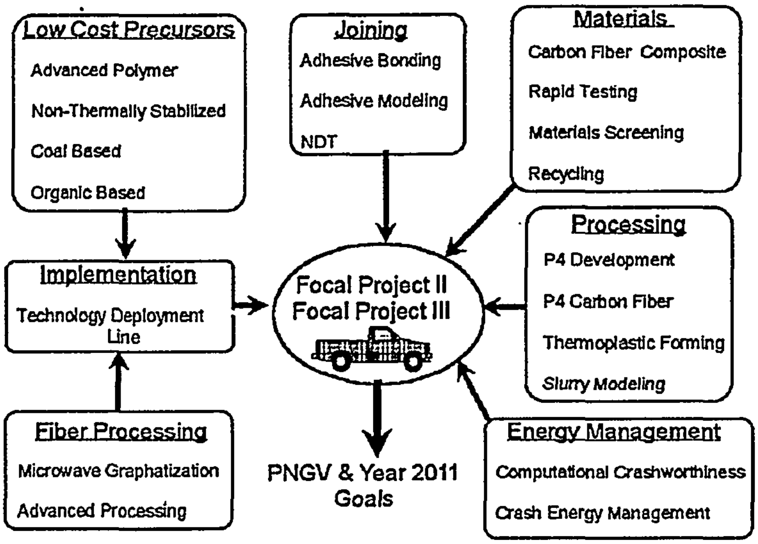
The second focal project was aimed at developing and demonstrating the methods needed to produce large, complex composite automotive structures. The goals were to produce a generic pick-up truck box inner and tailgate structure showing 15 parts/hour production rates, 25% mass reduction compared to steel, part performance equivalent to steel and cost-competitiveness with current structures. This program includes joining technologies, durability testing and design development. All program goals have been met and durability testing is currently occurring.

Key elements of focal project II were the development and fielding of the P4 preformer for rapid, automated glass fiber preforming and the refinement of the compuform process. The P4 process was used to make single piece preforms for the entire pick-up truck bed and the compuform process was used to make the tailgate preforms. Also critical to this effort was the development of durability, bonding, and crash energy management design methodologies. The truck bed assembly is designed to withstand temperature, load and environmental extremes while meeting crash standards with adhesive bonds, not mechanical fasteners, holding the structure together.

CARBON FIBER EMPHASIS

As more agressive DOE weight reduction goals were defined, it became apparent that carbon fiber based composites were serious candidates for enabling those goals to be met. Carbon fiber based composites are restricted in automotive industry use due to the high current cost of carbon fiber in comparison to other potential vehicle structural materials. Additionally, the comparatively small size of the carbon fiber and carbon based composites industry has resulted in limited design, durability, processing and joining technologies for using carbon fiber. Figure 1 illustrates the current DOE automotive materials project portfolio which is aimed at developing core carbon fiber technologies to the extent that this class of materials will become an economically viable alternative for domestic automotive designers.

FIGURE 1. DOE Transportation Composite Materials Program



The greatest cost factors in carbon fiber production are the high cost of precursors (45-60% of production costs) and the high capital equipment costs (20-35% of production costs). In response to this, DOE has developed and coordinated with the ACC an addition to the research portfolio aimed at reducing the cost of carbon fibers. The current research portfolio includes the development of non-traditional precursors, novel production methods and a means for fully developing these advances in a demonstration user facility which will be available to potential suppliers. This research program will culminate in the development of a third focal project. A brief description of the projects in this research portfolio follows. A roadmap for long term program direction is being formulated.

RESEARCH PORTFOLIO

1. Materials

Carbon Fiber Composite. Provide mechanical data, durability data and recommended design allowables for carbon fiber reinforced composites. Fatigue, fracture, creep, temperature and solvent extremes with synergistic relationships are being developed. This will deliver design guidelines, design protocols and computer based design tools.

Rapid Testing. Develop a database, test procedures and test fixtures to investigate the fundamental damage mechanisms in composites as a function of specific, varied mechanical loading with concurrent environment exposures.

Materials Screening. Evaluate various fiber/resin combinations for function, durability and processability.

Recycling. Determine the technical and economic feasibility of various recycling options for thermoplastic and thermoset composites.

2. Joining

Adhesive Bonding. Develop new methodologies to characterize the durability response of composite and composite-metal joint. Effects of temperature and solvents on the mechanical response are being evaluated. Test procedures and fracture based design guidelines are being developed.

Adhesive Modeling. Develop time dependent fatigue fracture models of adhesive failure paying particular attention to the effects of temperature and solvents. Provide design guidelines and computer based tools for designing adhesively bonded joints for long term durability.

Non-Destructive Evaluation. Develop non-destructive evaluation techniques that are sufficiently fast, robust in manufacturing environments, accurate and cost-effective to be suitable for on-line inspection of automotive structures with adhesive joints.

3. Processing

P4 Development. Fully develop, implement and optimize the proprietary P4 process. Use this technology to make focal project II preforms.

P4 Carbon Fiber. Develop methods for using the P4 process with carbon fiber. Includes all equipment modifications.

Slurry Modeling. Advance current water slurry processes to make them usable for manufacturing automotive structural components. Develop 3-D computer models to fully understand and be able to tailor the manufacturing process.

Thermoplastic Forming. Develop high rate forming processes for shaping carbon fiber reinforced thermoplastic impregnated composites into automotive shapes. Formability limits will be determined along with design parameters and the ability to predict in-service performance.

4. Energy Management

Computational Crashworthiness. Develop analytical and numerical tools that efficiently predict the behavior of carbon fiber based composites in vehicular impact conditions. Develop constitutive material models for random fiber, directed chopped fiber and engineered fabric materials.

Crash Energy Management. Experimentally determine the effects of material, design, environment and loading on macroscopic crash performance and develop predictive tools. Develop design concepts for application.

5. Low Cost Precursors

Advanced Polymer Precursors. Investigate the use of various high carbon polymers as potential carbon fiber precursors.

Non-Thermally Stabilized Precursors. Develop precursors which are stabilized by methods other than the application of heat energy.

Coal Based Precursors. Investigate the use of coal based pitch as a low cost precursor source for the production of carbon fiber.

Organic Precursors. Investigate the use of recycled materials as precursors and the use of organic materials as precursors for the production of carbon fiber.

6. Fiber Processing and Implementation

Microwave Processing. Complete development of technology for using microwave energy for the production of carbon fiber to reduce equipment costs, production times, and develop fibers with unique properties.

Technology Deployment Line. Develop a user facility where innovations in carbon fiber production can be implemented and optimized. It will provide a site for current and potential fiber producers to fully develop new technologies before implementing changes into production facilities.

Advanced Processing. Optimize current carbon fiber production methods.

7. Focal Projects

Focal Project II. The goal is to produce a generic pick-up truck box inner and tailgate structure showing 15 parts/hour production rates, 25% mass reduction compared to steel, part performance equivalent to steel and cost-competitiveness with current structures. This program includes joining technologies, durability testing and design development.

Focal Project III. Details are proprietary.

PARTICIPATION IN THE PROGRAM

Innovative ideas that will further this research portfolio and aid in meeting DOE and ACC goals are sought on a continuous basis. A more extensive blueprint for future research efforts will be available in July of 1999. Please submit ideas in writing to the author at P. O. Box 2009, M/S 8039, Oak Ridge, TN 37922 or WARRENCD@ORNL.GOV.

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