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Lightweight Materials For Transportation

Program Plan

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per
Office Of Transportation Materials
Energy Efficiency and Renewable Energy
U.S. Department of Energy
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LIST OF ABBREVIATIONS AND ACRONYMS

AMPP	Advanced Materials and Processing Program
ARPA	Advanced Research Projects Agency (Previously DARPA -Defense...)
ATP	Advanced Technology Programs
bbl	barrel
CRADA	Cooperative Research and Development Agreement
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
DOE-OR	DOE - Oak Ridge Field Office
DP	Defense Programs
EMaCC	Energy Materials Coordinating Council
ES&H	Environment, Safety, and Health
FCCSET	Federal Coordinating Council for Science, Energy, and Technology
FEA	Finite Element Analysis
FRP	Fiberglass Reinforced Plastic
HDT	Heat Deflection Temperature
HSS	High Strength Steel
LCP	Liquid Crystal Polymer
Maglev	Magnetic Levitation (usually trains)
MM	million
MMC	Metal Matrix Composites
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Evaluation
NES	National Energy Strategy
NIST	National Institute of Standards and Technology
NVH	Noise, Vibration, and Harshness
ORNL	Oak Ridge National Laboratory
SAE	Society of Automotive Engineers
SMC	Sheet Molding Compound
SPF	Superplastic Forming
USAMP	United States Automotive Materials Partnership
USCAR	United States Council for Automotive Research

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EXECUTIVE SUMMARY

Materials technology has been identified as critical to our nation. Advances in structural materials and associated processing techniques are of key importance to military, space, transportation, consumer goods, and other industries. Materials science has recently been brought into the limelight as a focal area for the sustaining and growth of our economy, improvement in our national competitiveness, and reduction of our impact on natural resources. In the transportation sector, there has been a sustained drive to reduce weight, number of components, and process waste through applications of improved materials and processes. This underlies the overall goal of optimizing efficiency. Most recently, the visibility of environmental impacts has been leading to a long overdue focus on lifetime efficiency. This lifecycle approach to optimization is beginning to be recognized by the transportation industry as a significant factor in its approach to materials and processing.

Automobiles account for almost two-thirds of the nation's gasoline consumption and about one-third of the total U.S. energy use. The \$200 billion automotive industry uses 23 million *tons* of material annually to produce about 12 million vehicles, employing one out of seven American workers. It accounts for approximately \$40 billion of our foreign trade deficit. The future of the U.S. automobile industry is the future of America in an economic, environmental, and social sense. Gaining independence from foreign oil, reduction of pollution, and increased efficiency in utilizing natural resources require a dramatic change in the automobile industry. Efforts to regulate this have included stricter Corporate Average Fuel Economy standards and reduction in allowable emissions for current gasoline type vehicles. Recent government and industry programs have included promotion of alternatively fueled vehicles, including methanol, natural gas, electric, and hybrid vehicles.

It is estimated that 75% of a vehicle's fuel consumption is directly related to factors associated with weight; the additional 25% is associated with air drag. The impact of a 25% weight reduction of current vehicles would result in gasoline savings of 750,000 bbl/day, or about 13% of U.S. gasoline consumption, as well as 101 million tons/year reduction in CO₂ emissions. Until now, no direct programs aimed at vehicle weight reduction existed outside of the auto companies, and the utilization of advanced materials and manufacturing technologies developed for other applications, such as defense and aerospace programs, was limited.

Automobile companies have done an exceptional job of vehicle weight reduction over the last two decades. The average weight of a vehicle has been reduced nearly 25% while doubling fuel economy, maintaining or improving handling and performance, improving all aspects of safety and reliability, and adding many style and comfort features demanded by consumers. Benefit has been gained from vehicle downsizing, as well as from optimization of the performance and design of materials and components. However, the automakers estimate that existing vehicles are near optimum with the choices of materials and manufacturing methods currently employed. A major new effort is required within the industry to 1) enhance processing of traditional materials to allow further weight reduction; 2) develop new processes and material forms so that existing lightweight materials become more cost-effective for increased use in mid-size sedans; 3) developing recycling technology

for in-plant and scrapped vehicle waste; 4) develop capabilities to computationally simulate processes, materials, and components, allowing design, performance, and material use optimization in vehicle systems and sub-systems as well as in individual component production; and 5) accelerate the development and introduction of new materials to automotive applications.

Two families of materials are most generally applicable under this proposed effort: metals and polymers. The application of ceramics is covered under the existing Ceramic Technology Program of the Department of Energy Office of Transportation Materials (DOE-OTM). Within the metal group, high-strength steels, aluminum alloys, and magnesium alloys are considered highest priority, with titanium alloys, intermetallics, and metal matrix composites also desirable for longer range applications. General needs include process modeling, process development for improved quality and performance, alloy development to enhance processability and properties, process development to transition typical defense/aerospace processes to automotive process demands, and development of joining techniques. In the polymers area, unreinforced and reinforced plastics are considered highest priority, with advanced high-strength, high-stiffness materials, such as rigid-rod polymers, desirable for future development. Also, since polymers are generally synthesized from petrochemicals, alternate feedstock investigation may be considered for longer-term development. Needs in polymers include improved process modeling to optimize design and performance, development of rapid, production scale processes for reinforced plastics, low-cost and durable tooling, development of low-cost materials and components, especially advanced reinforcing fibers and high performance resin systems (including exterior materials which provide Class A surfaces), improvement in the understanding of materials in crash performance, recycling of materials, and improvements in accelerated testing and modeling of durability and lifetime performance, including repair methodology.

The Lightweight Materials (LWM) for Transportation Program Plan has been prepared by the Office of Transportation Materials in response to a request by the House Committee on Appropriations. It recognizes that a significant commitment to long-term, stable materials research and development (R&D) is required to realize the benefits of lighter weight vehicles, including economic, environmental and energy related benefits. Extensive input was obtained from the major U.S. automakers and from representative materials and component suppliers. Considerable interaction with the key members of the U.S. Automotive Materials Partnership (USAMP) has ensured consistency of technical direction. The program will support R&D activity at industrial sites through competitively bid subcontracts with cost sharing anticipated at 30-50%, with the higher amounts in process scale-up and manufacturing technology development. The recommended LWM Program will enable industry to develop necessary technology by utilizing their capabilities as well as accessing supporting technology at national laboratories, universities, ongoing program activity at NASA, DoD, DOT, NIST, etc., and thereby leverage industry resources through integrated team approaches. Many individual program efforts are currently in place that address small portions of the overall needs of the LWM Program, both within DOE and in other agencies. Cognizance of these and overall integration of research activities are planned as significant program management tasks. Because of the international nature of the automobile business, benchmarking of foreign technology and tracking of worldwide developments are also key program elements.

The LWM program is fully consistent with, and supports all goals of, the Advanced Materials and Processing Program (AMPP) as developed by the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET). The AMPP goals are to "Improve the manufacture and performance of materials to enhance the nation's quality of life, security, industrial productivity, and economic growth." The LWM materials technology developments are expected to have a significant positive impact on both conventional fueled vehicles, thereby supporting goals of the Energy Policy Act, and also act as enabling technology for the "clean car" proposed by President Clinton. The primary focus of this program plan is on the existing industry, advancing materials and technology through the current structure. For development of a truly "clean car", major advances in vehicle structural performance will be required, along with advances in powertrain technology. Additionally, new thinking about manufacturing and marketing of vehicles will be needed and public education about benefit/cost of vehicles will have to be addressed. These factors will affect materials developed for these "clean car" vehicles, and would impact R&D direction of this and other programs.

The automobile industry (automakers and material and component suppliers) will be the focus of material and process development and will be relied on for production-scale fabrication equipment. Development cycles for new vehicles are typically 3–5 years and rely on fully mature technology. Proposed new materials and processes, therefore, have long lead times before impacting vehicle weight reduction, and rapid implementation of the program efforts to existing internal combustion vehicles should be considered to maximize benefit to the public. Additionally, alternative-fueled vehicles, notably electric and hybrid vehicles, will rely heavily on advanced materials to minimize the structural weight. This is required to reduce the weight of batteries and/or additional drive systems, allowing comparable performance at lower costs.

The recommended financing option for the Lightweight Materials Program includes federal funding of approximately \$246 million for the first 5 years of the program, with additional industry cost sharing of \$202 million, for a total of approximately \$448 million.

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1. INTRODUCTION

When incorporating a gasoline engine into a coach in 1886, Carl Benz opened a new dimension in individual mobility. Since then, automobiles have been developed to their present state while giving birth to one of the most powerful industries of our day. The \$200 billion U.S. automotive industry uses 23 million tons of material annually to produce about 12 million vehicles. Although the first-generation automobile was made of wood, steel was quickly used to replace the wood structure and before long aluminum was used as a replacement for some steel components. Today, steel and aluminum dominate the load-bearing structure of the automobile. Plastics and composites have found increasing use in modern automobiles but are still primarily limited to non load-bearing applications.¹

The automotive industry is driven by new emissions and fuel-consumption requirements, as well as the demands of a more sophisticated consumer and the pressure to compete in a worldwide market, to step up their evaluation of new, lighter weight materials for vehicles that are more fuel efficient.² Weight reduction has become increasingly important, and some analysts indicate the average automobile will have to be lightened by 500–700 lbs. in order to meet future anticipated fuel efficiency requirements.³ To stay competitive by providing greater customer satisfaction, the automotive industry is striving for improvements in safety, comfort, economy, reliability, and producibility, and for a reduction in environmental pollution during production, in use, and after vehicle life.^{4,5} New materials to meet these demands must offer advantages in raw material cost, processing cost, performance, range of uses, environmental protection, quality, reliability, and crashworthiness.⁶

Weight savings and design flexibility are primary reasons to develop alternative materials. New materials can reduce weight by 25–50% which can yield significant benefits in fuel conservation and emissions reduction.⁷ The raw material or the production costs of the alternate materials, however, often make them impractical for many applications.⁴ The challenge is to design lightweight materials that are cost-effective, stronger, more reliable and safer. With quality, price, safety and efficiency now being extremely competitive between automakers, and downsizing having reached a limit that consumers are balking at, the idea of passenger/vehicle integration is improving in acceptance. Here the vehicle is a more logical extension of the customer rather than simply an assemblage of parts. As the average person continues to increase in size, vehicles must be made to accommodate his needs. Lightweight materials will allow the designers flexibility in meeting demands within the spectra of regulations and fuel economy requirements.

One key to developing any automotive material is to consider the recycling of scrap, whether it is created during the production process or after the vehicle is discarded. Europe is most actively pursuing recycling technology for automobiles, where regulations call for a 25% rate of plastics recycling in cars by 1994.⁸ Recycling technology must include the selection of materials and joining technology that favor recycling, the development of methods for recycling dismantled car components, and the development of production recycling processes for scrap.⁵

Successful lightweight materials programs have shown the need for simultaneous consideration of material, process, design, and manufacturing techniques. Lightweight

materials must be designed for—not simply substituted.⁹ An extensive body of knowledge is needed about alternative materials to give designers the flexibility to design for lightweight systems. Such knowledge is pre-requisite to lightweight materials competing with steel.⁵ Fully characterizing the entire performance spectrum of new materials can be met only by an intensive research and development effort.

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.¹⁰ The U.S. economy also depends to a large extent on the price of petroleum. By improving automotive fuel efficiency, the United States can lessen the impact that foreign oil prices have on our economy. In addition, reduced emissions from reduced fuel consumption will provide a cleaner environment for future generations. New generations of lightweight automotive materials which include aluminum, aluminum alloys, polymer composites, metal composites, magnesium alloys, intermetallics, and ceramics can pave the way for a more competitive U.S. auto industry while improving fuel economy and reducing emissions. This can provide the U.S. automotive industry an advantage in their fierce competition with automakers from Japan and the European Economic Community. Such a large scale research and development effort for lightweight materials will require the cooperation of the government and the U.S. automotive industry and the leveraging of the wealth of talent available at universities and the national laboratories.

2. AUTOMOTIVE MATERIALS - INDUSTRY NEEDS ASSESSMENT

The primary goal of the Lightweight Materials Program is to address needs *identified by industry* where existing and potential advanced materials and processes technology can impact concepts for lightweight vehicles. Appendix C, "Publication Review," identifies published approaches to the materials questions of the automotive industry and gives examples of where materials or process technology has been used to reduce weight. This section will specifically document automotive needs identified through direct interaction with the industry. This interaction included site visits and follow-up discussions, hosting of a display and interviews at the Society of Automotive Engineers Auto Show, and industry input to a Lightweight Materials Workshop held in June 1992 in Detroit. In addition, General Motors and Chrysler held Technology Exchange Shows where key personnel were able to give direct input to current and future materials needs. At least three site meetings were held with each automaker to define, review, and comment on research needs. Appendix D identifies the primary contributing organizations. Several small businesses also provided input both at the SAE Show, as well as through telephone contact after the Program Plan announcement was published in trade journals. Two related workshops, computational simulation of materials performance and coatings needs of the automotive industry, provided input to the program plan.

A recent development within the industry has been the formation of the United States Automotive Materials Partnership (USAMP). This is a Chrysler, Ford, and General Motors consortium reporting under the US Council for Automotive Research (USCAR), with the express goal of developing precompetitive materials technologies for improving vehicles. Their preliminary R&D agenda is reflected within this program plan, and it is expected that USAMP will be a critical resource for the LWM Program.

Over the past 15 years, the average weight of a vehicle has been reduced by 20-25% from approximately 4000 lbs to just over 3000 lbs. Although this seems impressive, further examination shows that most of the reduction (~15%) occurred between 1978 and 1980, with only a slow but steady decrease in weight thereafter. Projections of weight reductions necessary to enable automakers to meet upcoming anticipated legislative standards currently range from 30% to 35%, with a 2000 lb vehicle projected as typical. At the current rate of change, this would take more than 20 years to accomplish. However, vehicle materials and production technology have not changed substantially in the last decade, and many new materials and processes have been developed that may significantly impact the vehicle as we know it. The barriers to increased use of advanced materials in almost all cases are cost and manufacturability, and recently, an increasing emphasis on recyclability and environmentally benign processing. Implementation of even the most developed lightweighting technologies on a broad scale is not currently feasible, based on vehicle cost to the average consumer. The development of LWM technology is intended to aid industry in addressing these concerns, as many of the demands being placed on the industry are based on societal and regulatory pressures in emissions, mileage, and environmental friendliness.

The potential national fuel savings, based on a 25% weight reduction of existing vehicles, is estimated at approximately 750,000 bbl/day, or about 13% of the U.S. gasoline consumption. This also results in a 101 million ton/year savings in CO₂ emissions. There is a tradeoff to acquire this benefit as most materials associated with lightweighting are more

energy intensive to produce and therefore tend to have much higher raw material costs. Although recycling, especially of materials such as steel, aluminum, and magnesium, reduces the energy penalty, issues regarding raw material supply need to be addressed in the life-cycle energy balance. Until the technologies and infrastructure for recycling are established, applications of advanced composites (polymer and metal matrix) and polymers will be based primarily on the use of virgin feedstock.

2.1 AUTOMOTIVE WEIGHT REDUCTION OPPORTUNITIES

Downsizing was used primarily during the 1970s and early 1980s for vehicle weight reduction, but recently the industry has seen a much larger demand for the mid- to full-sized sedan, with corresponding demand for performance, safety, and comfort systems. These all add weight to the vehicle and restrict fuel economy within reasonable cost guidelines. Automobile companies feel that existing vehicles are near optimum in weight with current materials and manufacturing methods. Caught between consumer demands and regulatory requirements, and facing very stiff competition from overseas, the auto industry feels the need for accelerated development of materials and processes that can:

- meet consumer requirements of quality, performance, and size;
- meet regulatory requirements of safety, emissions, and mileage;
- face anticipated regulations on recycling; and
- overcome international competition in areas of quality, style, performance, safety, mileage, and reliability.

Automotive weight reduction opportunities have been separated into two general categories—*body and chassis* and *powertrain*. This provides a convenient method to describe the various materials and technologies associated with well-recognized components, as well as allowing division into application area rather than material type. This is primarily for purposes of understanding specific needs in the context of the vehicle. It is important to note that the design, materials, processing, assembly, and recovery must be integrated considering a total systems approach, with the material system being a part of the vehicle system.

2.1.1 Body and Chassis

Needs for the body and chassis include structural performance and safety; appearance; durability; and packaging. Aspects such as aerodynamics, performance, safety, comfort, and access must be met concurrently—all at extremely low cost. With the total material value of a vehicle at about \$4/lb, and the powertrain and electronics being relatively expensive, the body and chassis typically need to be well below this figure.

Current material of choice for the auto body is carbon steel, with some usage of high strength steels (HSS). Auto companies have studied increased applications of HSS extensively, and see a possible 10% component weight reduction with maximum use. Aluminum alloys represent a significant opportunity, especially in space frames, interior and exterior panels, such as floor pans, hoods, deck lids, etc. Weight savings estimates range from 25 to 55%, with numbers being highly company dependent, but with a significant cost penalty.

Fiber reinforced polymers (FRPs) represent similar potential for weight savings, from 25-65%, and can be applicable for all body components (higher estimates include very costly raw materials such as carbon fibers.) Fabrication methods using FRPs allow the body to be made in 5-20 large, functionally integrated parts, suggesting potential cost effectiveness for future vehicles. In addition, closure panels for space frames can be made of FRPs. Interior materials offer potential for weight reduction in areas such as seats and seat supports, instrument panels, and miscellaneous components including steering wheels and columns, latches, pedals and their mechanisms, etc.

Chassis components, including brakes, wheels and suspension systems, could provide very significant benefits to weight reduction of the overall vehicle. Reductions in unsprung weight allow further weight reductions in support and bracing structures, and give the automakers added design flexibility. Improved corrosion resistant materials and further development of processing operations, such as hydroforming, for exhaust materials would result in additional weight reduction.

2.1.2 Powertrain

Powertrain requirements are built around the traditional gasoline-based engine and associated drive system. However, performance benefits gained here will likely be applicable to electric, hybrid, and alternative-fueled vehicles also. Needs are in total mass reduction of engine and drive systems, with a move from traditional ferrous alloys to aluminum, magnesium, metal matrix composites, intermetallics such as titanium aluminides, and ceramics. Important reductions in reciprocating mass and lowered friction are required for improved engine efficiency. This can result in improved noise, vibration, and harshness (NVH) and allow for improved packaging, thus saving secondary weight. Needs and applicable materials have been noted in Figure 2.1, along with a brief summary of research opportunities. Expanded research opportunities are listed in Appendix A.

Fig. 2.1. Automotive weight reduction opportunities

	Iron & HSS	Al alloys	Mg alloys	Other metals-Ti, metal matrix, aluminides	Polymers	Fiber reinforced polymers
Body panels	Ductility, Consistency, High volume processes	Low cost sheet, Repair, Joining, Process models	N/A	N/A	Recycle, Process models, Heat stability	Low cost fibers, High rate processes, Process models, Recycle, repair
Support structures	High volume processing, Adhesive bonding, Ductility	Adhesive bonding, Welding, Process models	Joining processes, Casting models	Casting, especially thin sections, Joining	N/A	Design modeling, Crash energy mgmt, Joining
Drivetrain	High volume processing, Adhesive bonding, Ductility	Wear resistance, Common alloys	Casting models, Wear resistance	Cost & hi-vol fabrication	N/A	Design, High rate processes, Low cost parts
Engine	Process models, Consistency	Wear resistance, High temperature strength, Casting models	Cost, Wear resistance, High-temp properties	Ductility, Machining/wear, High-temp properties	Hi-temp props, Durability prediction, Process models	N/A

2.2 TECHNICAL CHALLENGES FOR WEIGHT REDUCTION

Typically, there is a 4- to 5-year development cycle for a new automobile consisting of conceptual design, mechanical design and analysis, materials and process selection, tooling and equipment development/set-up, product manufacturing and assembly validation, and finally, production operations. Recently, this cycle time has been reduced through concurrent engineering practices. Very little time is allowed for development of materials and processes, because changes in these areas have significant effects on both up- and down-stream operations, with the potential for significant delay and/or negative consequences. For the design teams to accept a new material or process, it is essential to have no risk associated with manufacturing and use, at the time the commitment is made. Hence, both materials and manufacturing technology have to be mature for the design teams to buy into them. This leads to a long development cycle for any new material and/or process, because crashworthiness, durability, aging, life-time performance, and other extended lead-time factors need to be well understood, prior to entering the four to five year development cycle. Most of the new material development efforts occur at supplier, research, or engineering staff organizations. This has resulted in development of some materials with potential for vehicle weight reduction. Several factors have hindered this development, including limited funding available for material and process research, product requirements being based on what steel has done in the past rather than customer and functional requirements, and a lack of strong driving forces for new materials applications (in the form of realistic fuel prices, consumer demand, financial benefit to corporations, etc.). The issue of fuel prices has been noted several times, primarily by supplier organizations. The industry notes that component manufacturing and assembly energy usage is a small fraction (about 10–15%) of the total energy consumed in a vehicle's lifetime. Hence, from an energy balance, lightweight materials are favored in the automobile. However, their high raw material costs currently cannot be recovered by the automakers. Consumers have no social and economic reasons for favoring higher cost, lightweight, more fuel efficient automobiles.

Examination of the specific materials needs can be broken down into two categories, metal-based and polymer-based materials. Certain generic needs are noticeable across-the-board and have been identified in most, if not all, studies on materials for any industry. The fundamental need is *understanding the science of materials synthesis, materials and component processing, in-service performance of components, and recycle of materials*. It has been widely stated that the only way the automotive companies and their suppliers will improve international competitiveness is to develop and retain rights/control over process and fabrication technology. The two issues that the automakers are most concerned with, cost and quality, can no longer adequately be addressed via the traditional trial and error or experimentation loop. Time constraints on vehicle development, the need for optimized components, the high cost of gearing up, and very high demands on performance, appearance, and durability indicate that new materials and processes will have a very difficult time breaking the barriers of experience and knowledge base held by traditional materials. The technology developed within the Lightweight Materials Program is aimed at addressing these issues and includes predictive and modeling capabilities to aid in accelerated development. Application of new materials and processes requires incorporation of manufacturability, durability, and recyclability as early as possible in the development program. A critical bottleneck for new materials and processes has been identified in "as-manufactured

properties," relating to the need to use processes, components, and conditions that mimic production lines in the determination/verification of performance models.

2.2.1 Challenges in Metallic Materials

2.2.1.1 Cast Iron and Steel

Steel, long the mainstay of automotive fabrication, is not often thought of as a lightweight material. However, the auto companies have identified improvements in steels and cast irons as being one of the near-term opportunities for vehicle weight reductions. Because of the quantity of steel usage in a vehicle, use of HSS and optimization of cast iron to reduce component weight can have a large impact on overall vehicle weight. These improvements may be implemented very rapidly due to the familiarity of the auto industry in working with steels and the lack of major changes in technology. Typically, need times for results of research are stated as 1 to 3 years.

Specific items identified include stamped steel sheet for the vehicle body and chassis. Although this process is thought of as mature, all automakers have noted that the process physics of stamping are not well understood, and process models that allow them to optimize their operations are not well developed. Factors that are considered important are analysis and predictive behavior of the sheet steel, based on heat treatment, microstructure, surface hardness, desired finishing, local process conditions, etc. This effort also includes the development/optimization of tailored blanks. The need for higher-temperature, high-strength, corrosion resistant steels for powertrain components was also noted. These materials, or replacements for these materials, would allow lighter sections to be used for wear and rotating parts, and thus have a multiplication effect on weight reduction throughout the powertrain. Design flexibility due to lower corrosion presents the possibility of removing/optimizing seals and packing materials. This could potentially reduce the package requirements, which almost always leads to weight savings. Higher temperature rated steels would allow thinner sections to be used in some exhaust applications, and also remove the need for heat shields elsewhere.

Cast iron could offer potential weight reductions through modeling to obtain premium quality castings. Important factors include process development and melt control to allow thin wall grey, compacted, and nodular irons, especially with guarantees of key mechanical properties in critical areas.

HSS has been an important contributor to the weight-savings gain over the past 10 years. Some automakers feel that further benefit of up to 15% per component is possible with improved consistency of material and improved formability. However, others feel that HSS section thicknesses are about minimum due to stiffness limitations, and that only 4% or less gain is likely. One reason for these differing views may be the source of HSS, since foreign suppliers reportedly provide more consistency than current U.S. suppliers. Improved formability and useful process models could potentially allow high-strength steels to replace mild steels in other areas of the automobile, thereby contributing to weight reductions. Improved reliability of joining is also considered a research need and would probably be more applicable as section thicknesses are further reduced.

2.2.1.2 Aluminum

Aluminum is considered the next generation material for major automotive structural applications. All companies are working on an aluminum, hybrid aluminum/steel, or aluminum/composite vehicle for production purposes. The significance of aluminum lies in a potential weight reduction of 25–55%, depending on information source and material usage. Although it appears to provide an excellent route to weight reduction, material cost and current worldwide supply limit its application. The real need is for broad application in average, mid-line sedans where the passenger miles are greatest and energy savings will be maximized. Several components on U.S. autos have been made of aluminum in the past, with Ford apparently being the largest auto consumer of wrought aluminum in panels for the Crown Victoria, Marquis and Town Car. Some recent foreign sport vehicles, including Honda NSX, Nissan and Jaguar vehicles, have made extensive use of aluminum. As aluminum has also made inroads into under-the-hood applications, the time is approaching when replacement of most steel will be possible for certain models. Automakers feel that the Japanese will insert all-aluminum vehicles into the mid-line vehicles first, although Ford has demonstrated extensive use of aluminum on a Taurus sized model recently. Honda, after introducing aluminum on the Accord hood, has plans to expand aluminum panel applications in that vehicle. This will increase the pressure for U.S. automakers to compete with similar lightweight vehicles, and several issues related to application of aluminum have been identified.

Four items appear to be consistent among automakers for widespread applicability of aluminum in the area of body panels and structural members: (1) price, (2) formability process models, (3) reliable joining techniques, and (4) coating technology. One other item which appears selectively is actual formability (experience as opposed to modeling), with some companies claiming full knowledge and others saying it is a definite need. Aluminum is expensive as compared to steel; however, it has found major applications in engine blocks and components, because of the large weight savings and thus improved energy efficiency. The benefit of using sheet aluminum in the body areas is as significant, but because of combined cost, formability, joining, and coating issues, its use has not progressed as rapidly. Modeling of the forming process, joining and coating needs are common throughout the automotive industry. Modeling of the forming processes is a parallel need to the steel sheet-forming modeling, with different material and process parameters. Preferred joining methods at this time include adhesive bonding and edge crimping, and issues such as fatigue, failure mechanisms, and lifetime behavior are not well understood. With regard to the coating of aluminum, some of the issues include adhesion to the substrate, requirements and methods for surface treatments, effects of the bake cycle on aluminum heat (especially when there may be many different heats in the vehicle), substrate corrosion resistance under various states of normal use, and coating for galvanic corrosion protection including effects on subsequent joining. A strong focus on developing material property and durability databases for aluminum sheet, forgings, castings, and extrusions is needed. Gaps in the available property and design information need to be identified and addressed to the satisfaction of the auto designers.

In other more general areas, sheet-forming process technology, such as superplastic forming (SPF), has been identified as a highly desirable research need. Specifically, alloy development for low-cost, high-rate SPF aluminum has been identified by the USAMP as a

R&D goal. Also, improved toughness and corrosion resistant alloys could expand applications in chassis parts, with long term mechanical performance being a key need. Additionally, an education process relative to repair shop techniques will be required, which may include development of new techniques for easy and reliable repair, and simple non-destructive evaluation (NDE) technology for damage identification.

Aluminum casting R&D needs identified include 1) rapid prototyping mimicking final production quality components, 2) modeling to allow optimal design of materials, components, and tools, and 3) property description as a function of processes, microstructure and defects, including effects of recycled material. In the powertrain area, materials research needs have been noted in reliable wear-resistant castings, eliminating the need for liner inserts, coatings, etc. Technology for nonlined cylinders does exist but is not well understood, and there is a lack of confidence in this technology due to earlier poor experiences in production vehicles. Wear-resistant alloys could enhance use of aluminum in prop shaft connectors, gears, and other friction controlled applications. A significant need has been noted to reduce material and process costs to allow wider usage. A major component of this would be realistic process models to provide component and fabrication optimization.

2.2.1.3 Magnesium

Magnesium is viewed by all the automakers as a very promising candidate material for vehicle weight reduction. However, the automakers opinion is apparently that cost is too high and supply is too limited, although magnesium suppliers have indicated a willingness to increase supply to meet volume demand. Although cost per pound is high, material properties and low density combine to make magnesium an attractive alternate in many applications. Currently projected percentage growth in magnesium usage is significant, however absolute quantities are still only near 2–5 lbs per vehicle. Magnesium has performed well in housings and transfer cases, and there is a desire to investigate magnesium for use in engine blocks. Areas of research needs are in alloy development for improved elevated temperature properties, wear resistance and corrosion resistance (especially in combination with other properties); modeling of the casting process (primarily as relates to forming high integrity, high ductility parts); and development/education of the supplier and castings infrastructure. R&D needs for magnesium casting essentially parallel those of aluminum alloys noted above.

Magnesium has excellent potential for use in housings in underhood and powertrain applications. Improved wear resistance would expand potential for use in latches, impellers, guides, and seat mechanisms. Improved elevated temperature properties would allow expanded use in transmissions and brake components. The modeling requirements overlap those of steel and aluminum in that effective three-dimensional casting models are required for mold and part optimization, improving design turnaround time, optimizing part weight, and improving part quality. Supplier base would benefit from improvements in molten metal handling and simplification of internal scrap recycling. Some automakers are investigating magnesium for use in engine blocks and related components, applications which rely heavily on developing the process models, wear-resistant alloys, and lower cost materials. This could provide a significant benefit to existing vehicle weight. Lastly, methodologies and hardware systems for joining and fastening techniques have been noted as needs to allow expanded

application of the corrosion resistant magnesium alloys.

2.2.1.4 Titanium, Intermetallics and Metal Matrix Composites

These materials come under the "highly desirable and we wish they were lower cost" viewpoint by the automakers, with cost of both material and fabrication being major contributing factors. Especially for titanium, significant efforts in cost reduction are desirable. Titanium and intermetallics have been considered for powertrain applications, with research needs driven by processing cost. Goals are to develop net shape forming processes to very close tolerances for both materials and to develop U.S. sources of free machining titanium alloys. Relative to alloy development, both improved wear resistance and high-temperature oxidation resistance are desired. Additionally, development of joining techniques has been mentioned as a research requirement. Needs for titanium and intermetallics appear to be very consistent across the automakers, however, to our knowledge, little attempt has been made to quantify the potential benefits available with increased applications. Specific materials of interest include nickel-, iron-, and titanium-aluminides, with the goal of weight reduction in higher temperature, wear surface type applications.

In the auto industry, metal matrix composites (MMCs) typically refer to particulate reinforced aluminum or magnesium. The industry is generally developing prototype components and using some MMCs on race cars, but MMCs have not made any inroads on production vehicles due to cost and processing issues. Supplier companies feel MMC components will be specified in the near- to mid-term, with the auto companies seeing a gradual evolution cycle of use and experience with the new materials leading to further applications. To date, applications are so limited that the weight savings as a fraction of total weight is very small, and investment cost is difficult to justify. The particulate reinforced aluminums have become more attractive now due to a growing supply base that can meet automotive quantity demands. Their excellent mechanical properties and wear resistance make MMCs desirable for powertrain components, including drive shafts, as well as brake and suspension components. However, automakers have identified research needs in machining, net shape processing, new low-cost fabrication techniques, joining technology, and improved reliability of materials. As with aluminum, property and durability databases that meet designers demands are required.

Some limited interest exists in short fiber or whisker reinforced metals, but these are currently cost and process prohibitive. For future needs (20 years or more) research into low-cost processing of whisker and continuous fiber reinforced MMCs would be desirable, but automakers see this as occurring in the space and defense industries then gradually transitioning to meet their needs. One other class of metal matrix composites that has been mentioned is cermets, essentially a continuous porous ceramic preform infiltrated with metal. This material may have long-term interest but is still in its infancy as regards process and product development.

2.2.2 Challenges in Polymer Materials

There appears to be a widespread acceptance among the automobile industry that the

body and chassis of some future vehicles, especially niche market vehicles, will be made primarily of polymeric composites. Large weight reductions, 25–65%, have been identified as possible, and most of the current "concept" vehicles tend to be polymer composite. Because of the problems associated with electric and hybrid vehicles due to the battery weights, polymer composite structures are seen as critical to providing maximum performance. The industry has, however, identified four major drawbacks to widespread implementation of composites in vehicles: (1) design and analysis of composite vehicles, (2) low-cost materials, (3) production scale processes, and (4) recycle of composite components. Extensive research is required in all of these areas, with a heavy emphasis on process development, material performance, and cost optimization.

Design and analysis of composite structures will be critical to their implementation. The industry typically uses 3 to 9 months to build and validate a vehicle model/design using isotropic (metal) codes and properties. There are three distinct common needs in the composites design arena. The first is development of the relevant design criteria and computational models to describe composite behavior, based on component constituent properties and processing factors. The second is adaptation of composite design criteria to existing codes for full vehicle modeling including vehicle packaging, static analysis, modal analysis, impact, damage tolerance, and life predictions. The third is development and installation of the codes on parallel processing machines so that the time and costs associated with design efforts are minimized.

Materials and processes for use of plastics have advanced to a point where they are viable for most cosmetic and some structural auto applications, including large interior load-bearing structures such as the instrument panel, as well as exterior skins. For example, Saturn has shown the ability to produce low- to mid-line vehicles using plastic skins instead of metal skins. Currently, the primary research needs on existing materials are in process modeling of injection molding and sheet forming processes, leading to weight reductions through part optimization. Significant vehicle weight reductions will only be possible through extending applications to load-bearing members and development of thinner sheet components, both of which require higher performance materials. Higher performance will generally be attained through use of fiber reinforcements, both continuous and discontinuous. The auto industry has identified a need for low-cost, high performance reinforcing fibers, such as intermediate modulus carbon fibers, to complement the typically used low modulus glass fibers. Process technology to rapidly manufacture fiber preforms and infiltrate with liquid resin systems is needed, as well as development of interface treatments to optimize properties. To predict and control properties, modeling of all process factors is an important need. Mold development for low-cost tooling will be required, with considerations of tool life, surface quality, surface energy (for finishing), and component removal. Ceramic tools, ion-implanted epoxy tools, and nickel clad tools have been mentioned as possible research areas.

Development of higher temperature resin systems and ability to predict long-term behavior will increase applications in the under-hood and exhaust regions. This need extends to applications of composites for all lower body components which would be subjected to relatively large loads and possibly severe environments. Durability and lifetime prediction, even down to the basic need for test methods to determine performance, are necessary for widespread applications and will be a significant part of the required design methodology development.

Composites have been burdened by a historical low-volume image of modest quantities of specialty products. They have also traditionally been replacements for metals in certain applications, a focus that was pushed by early marketers in order to get business quickly. High-volume production capability has only recently been addressed, and the ability and need to turn out very high quality parts (performance and finish) at automotive production rates has not been developed. The automakers believe extensive research into process modeling and process development is required to realize the potential of composites. Additionally, they have noted that all other research and development into new materials must be focused on cost and quality optimization under high-rate production.

Recycle of polymers and composites is the most critical long-term issue facing plastics applications in automobiles. Some materials currently exist with recoverable value, but more than 95% of automotive plastic scrap now goes to landfills. The auto companies have recognized that large scale usage of plastics will not be possible without development of recycle technology and that the most desirable option is recycle back to the vehicle market product stream. Because most plastics are derived from petroleum products, it is not feasible to only consider reclaiming the plastics to usable energy (pyrolysis, incineration), rather consideration must be given to depolymerization and other feedstock recovery schemes. The auto companies have noted that the drive to plastics is primarily due to legislation on emissions and fuel economy, and also expect that U.S. legislation will follow European legislation in mandating that auto companies take ownership of and fully recycle old vehicles. The research needs in this area are very broad, including paint removal to eliminate contamination, development of polymer systems that may be reprocessed to their monomers, development of thermoplastic composite systems where the polymer fraction may be remelted and recovered independent of the reinforcement, design for disassembly, separation methods for mixed waste, improving properties of materials to eliminate the need for compounds, and a myriad of chemical process requirements to recover the necessary fractions.

2.3 ENERGY, ENVIRONMENTAL, AND ECONOMIC IMPACTS

2.3.1 Energy Impact

The National Energy Strategy (NES) has called for research to increase transportation fuel efficiency, to accelerate the introduction of alternative transportation fuels and vehicles, and to pursue new domestic transportation fuels and technology. It was noted that the transportation fleet consumes approximately two-thirds of the oil used by the United States. The NES recommended research and development on alternative fuels, hybrid and electric vehicles R&D (including battery development), and in new transportation technologies, see Table 2.1. The Lightweight Materials program addresses the need for a materials program aimed directly at weight savings. With approximately 25–30% of vehicle fuel used in overcoming air drag, and the remaining 70–75% used in factors directly associated with weight, the potential for energy saving through direct weight reduction becomes obvious. In addition, automakers estimate that electric and hybrid vehicles will have serious concerns over packaging and total weight because of the increased burden of the batteries and dual propulsion systems. Cost-effective, total system weight reduction is considered a critical need for high-performance electric and hybrid vehicles. The lightweight materials technology

developed in conjunction with industry and universities should become a key part of the national approach to energy conservation and reduction of dependence on foreign resources, thus aiding in achievement of NES goals.

Table 2.1. Funding levels for surface transportation R&D, FY 1991-1993 (dollars in millions)

Research area	FY 1991 Actual	FY 1992 Enacted	FY 1993 Requested
Surface Transportation Efficiency			
Transportation materials development	21.6	23.5	26.4
Heat engine development	15.8	16.8	17.5
Electric and hybrid propulsion	25.0	42.9	75.3
Other transportation efficiency	7.6	9.6	11.5
Intelligent vehicle highway systems	23.0	27.5	37.5
High-speed rail, maglev	12.0	20.0	28.0
High-performance communications	58.0	92.0	123.0
Total	163.0	232.3	319.2

The 1992 Delphi VI materials forecast⁶³ noted the auto industry predicting that 31 mpg is a potentially attainable mileage level by the year 2000. If so, the increase from approximately 27.5 mpg in 1992 would represent a gasoline savings of 460,000 bbl/day, or approximately 11% of consumption. Weight reduction is considered to account for only 20% of the improvement (see Table 2.2) showing limited new material usage in the overall fleet. Supplier industry estimates of 750,000 bbl/day gasoline savings have been made, based on 25% average current vehicle weight reduction. This would require intensive use of new materials. The supplier industry forecasts do not factor in vehicle cost, and the automakers are much more conservative in their estimates of new materials introductions. This gap, almost 300,000 bbl/day, between predicted implementation and potential savings can be addressed by the Lightweight Materials Program technology, especially with cost and environmental factors considered early in the R&D cycle.

Table 2.2. Sources of improved fuel economy

	Percent Total Fuel Economy Improvement	
	Model Year	
	1995	2000
Weight reduction	20	20
Engine efficiency	15	15
Downsizing	10	20
Drivetrain efficiency	10	10
Aerodynamics	9	5

2.3.2 Environmental Impact

Environmental benefit underlies all aspects of the Lightweight Materials technologies. Impacts will occur in fuel and emissions reduction, advances in recycling technology, and enhanced processing efficiencies. Net results should be seen in environmental cleanliness; in optimized fabrication potential—resulting in decreased resource demand; and in lowered waste energy and material.

With about 17 lbs of CO₂ produced per gallon of gasoline used, a 25% vehicle weight reduction would reduce CO₂ emissions by 101 million tons/year. Other tailpipe emissions, hydrocarbons, carbon monoxide and nitrogen oxides, are controlled by emissions standards which dictate catalyst systems. However, lowered fuel usage effects should result in reduction in quantities produced and thereby allow cheaper and possibly lighter catalyst systems. Concurrent goals of the LWM program in optimized fabrication and material usage will also lower demand on utilities and raw material supply, as future vehicles will be using possibly 1000 lbs less material per vehicle, and this will result in additional reductions in non-natural emissions. Although it is too early to predict these benefits, one program goal would be to track overall environmental impacts and benefits, helping provide future direction to this and other related materials industries.

The auto sector is one of the leaders of U.S. industry in material recovery, energy efficiency, and factory emissions. LWM technology will further enhance this as it supports a move toward flexible manufacturing and an overall systems approach to the component, material, and process design. Environmental benefits will occur due to both a reduced cycle time for introduction of the best materials and processes and optimization of the lifecycle cost of the vehicle. Increasingly, lifecycle cost will include all environmental impacts. The Germans are taking the lead in this area by introducing legislation governing the reusability of vehicle parts, recyclability of materials, and even potentially requiring buy-back of the scrapped vehicles at the end of their lifetime by the original automakers. Manufacturing technology will undergo substantial changes to adapt to this new environment. This program will play a cornerstone role in developing design, materials, processing, and recycle capability with industry.

Reinforced plastics applications have been shown to be one of the key future technologies for lightweight vehicles. Currently, although recycling of in-plant scrap is relatively high (estimates range up to 50% overall), recycling of "post-consumer waste" is very low, probably under 5% (and this is most likely due to parts re-use off of junked vehicles). The majority of plastics in scrap automobiles (approximately 200 lbs) ends up landfilled with the fluff fraction, which is approximately 700 lbs per vehicle. Automotive predictions of future use of plastics include a more than doubling in the next 8 years. Limited efforts aimed at the recycling problem exist, with the Europeans ahead in technology. Major programmatic emphasis is required on the recycle problem, with benefits spreading across all major industries. It is also important to note that the increased use of plastics will place demand on oil supply, as traditional feedstocks are petrochemical based. It is proposed that the future materials development efforts look at cost-effective alternative feedstocks for recyclable automotive plastics, to further reduce our dependence on limited oil resources. Finally, the infrastructure for recycle of materials other than steel, aluminum and specialty metals is not in place, and cost-effective technology for these industries is required.

2.3.3 Economic Impact

The automobile industry, as a whole, annually contributes almost \$200 billion in gross sales to the economy, accounts for about \$40 billion of the foreign deficit, employs 1 out of 7 American workers, has total sales of 10-15 million vehicles, uses 23 million tons of materials, consumes approximately one-third of the total energy used in the U.S. and uses two-thirds of our gasoline. Comparatively, the automobile has a low value per pound of material, typically about \$4/lb on a finished cost basis, with approximately \$2/lb value on weight saved. One reason for this discrepancy is consumer fuel prices, which many in the industry feel do not reflect the true costs of transportation including infrastructure, pollution, government regulations, and safety costs. As many of these associated costs are not immediately visible as transportation costs, consumers do not place high value on fuel economy and hence weight reduction, and preferences have moved back toward large, powerful vehicles in the last decade.

Several major drivers are seen by the automakers as impacting their need for lightweight vehicles. Regulatory factors on environmental and resource issues are creating intense pressure to change from traditional materials and processes. This is intertwined with the impact of global competitiveness, because overseas regulations are changing more rapidly than ours, and the foreign markets represent a larger and faster growing segment than the U.S. market. The health and survival of the U.S. industry depends on being globally competitive, and new, innovative materials and process technology is required to build and maintain a lead.

In addition to the automobile companies, the U.S. supplier industry stands to benefit greatly from Lightweight Materials technology. The raw material and component industries associated with new materials and technologies have access to the U.S. automotive companies, as well as serving all foreign automakers. Currently, the widely accepted view is that overseas companies lead in metals processing, with the ability to produce alloys and product forms with more control, consistency and quality than others. The plastics industry favors U.S. companies, especially in the performance plastics market, but the Europeans and Japanese are very close and are investing heavily in the reinforced plastics markets while U.S. interest appears to be declining. With the potential for major breakthroughs in both the metal alloy and reinforced plastics fields leading to substantial market share, the economic impact of advanced R&D in materials, processes, and product forms cannot be emphasized enough.

3. FOREIGN AND U.S. PROGRAMS

During the last half century, America's great technological strength has been a major driving force for its economic prosperity. The U.S. manufacturing and service industries have enjoyed a considerable lead over other nations in world markets. This comforting position, one to which we have grown accustomed, is under attack from intense international competition. In recent years, many U.S. technology-intensive industries have stumbled in the face of foreign competition.⁵⁹

The crucial importance of materials to industry is recognized by the governments of all principal trading partners and competitors of the United States. Each country has identified materials as a key technology and is taking an active role in deciding areas of emphasis that will enhance their industrial competitiveness.⁶¹ Governments in other major industrialized nations have used R&D incentives, public-private consortia, infrastructure programs, tax policy, trade policy, and regulations to improve the technological competitiveness of their industries.⁵⁹ U.S. initiatives have been primarily limited to tax policy, trade policy, and regulation. Worldwide, the most successful efforts combine funding with extensive public-private collaboration. U.S. science and technology policy has tended to focus primarily on support for basic research; the bridges from basic research to manufacturing have frequently been weak. Industry in other foreign nations, particularly Japan, exhibits a commitment not found in the United States to the use of advanced materials. Japan produces low technology consumer goods using high-tech materials and processes. The strategy is to give these materials a high profile and to develop a high-technology manufacturing base to capture the advanced materials markets as they mature.⁶⁰

The United States still has one of the finest research bases in the world, but its ability to commercialize technology and capitalize on market opportunities is being severely challenged. Government programs can have a major impact on industrial competitiveness by providing coordination, collaboration and funding for precompetitive research and development. The two largest components of the U.S. trade deficit are imported oil and automobiles. A well-coordinated government/industry collaborative program in Lightweight Materials for Transportation will go a long way toward improving our industrial competitiveness, as well as addressing energy and environmental concerns.

Although the U.S. materials research budget is relatively large, very little of the effort addresses lightweight materials, their processes, their economic production at automotive scales, and the myriad of technical issues facing new materials and applications. The Lightweight Materials program will interface with the military, aerospace, and energy programs to leverage technology and assist in crossing traditional materials and process boundaries, resulting in benefit to all sides of U.S. materials R&D.

3.1 FOREIGN COMPETITION

Materials research in support of industry is actively pursued by the governments of all principal trading partners and competitors of the United States. This cooperative relationship, in conjunction with very close ties between material suppliers and automakers,

has developed formidable competitors to U.S. industry. An important task of the Lightweight Materials program is to keep abreast of foreign activities and to benchmark the program against foreign standards in the use of advanced materials for automotive applications. Special attention will be given to recent German legislation pressing recycling issues.

3.2 U.S. PROGRAMS

To address the needs and opportunities in materials, the Federal government has initiated a multi-year, multi-agency effort to increase the effectiveness of the Federal R&D program in materials science and technology. The Advanced Material and Processing Program (AMPP) has been developed by the Federal Coordinating Council for Science, Engineering and Technology (FCCSET).⁶² Several proposed program enhancements from the DOE, DOC, DoD, DOT, and NASA are expected to contribute to "breakthroughs" in transportation. In addition, opportunities exist for transferring government technologies to industry in areas such as aluminum forming, advanced processing methods for all metals, computational analysis, composite forming, and advanced testing.

Current and planned federal R&D activities in materials science and technology for the selected agencies are briefly described in sections 3.2.1 to 3.2.5. The proposed 1993 program enhancements are included.

3.2.1 Department of Commerce

Materials R&D is conducted primarily by the Materials Science and Engineering Laboratory at NIST. The core program addresses scientific and measurement issues crucial to industry's success in exploiting the advantages of advanced materials, the development of process technologies to transform new advanced materials into viable products, and manufacturing processes that yield high-quality products at reasonable cost. DOC has historically had an industry focus, and supports advanced material technology through their Advanced Technology Program (ATP) industry grants. These cost-sharing, competitively bid subcontracts are very highly regarded in the automotive materials community, and are considered a premier example of cooperatively funded R&D. NIST monitors these grants and also conducts R&D in "intelligent" processing of advanced materials, research on advanced structural ceramics, and processing and performance of polymer matrix composites.

Table 3.1. DOC AMPP R&D funding by research component (dollars in millions)⁶²

AMPP Component	FY 91	FY 92	FY 93
Synthesis and Processing	13.1	13.9	18.0
Theory, Modeling, and Simulation	8.7	8.8	9.1
Materials Characterization	11.6	11.5	11.3
Total*	33.4	34.2	38.4

*Excludes funding for national user facilities/other.

3.2.2 Department of Defense

The DoD Materials Science and Technology Program is conducted by the Army, Air Force, Navy, and Defence Advanced Research Projects Agency. The DoD program is devoted to projects that support national security objectives. Materials and topics that are applicable to the Lightweight Materials Program include advanced alloys; ceramics; composites; polymers; coatings; corrosion; NDE; fracture analysis and testing; welding and joining; structural analysis, demonstration, and testing; and performance and durability. Where security permits, the results of DoD funded science and engineering research is available for technology transfer to industry, and is being supported through availability of dual use funds. The Lightweight Materials Program will investigate applicable DoD technology and R&D capability, and attempt to guide dual use funded efforts into programs that support complementary goals.

Table 3.2. DoD AMPP R&D funding by research component (dollars in millions)⁶²

AMPP Component	FY 91	FY 92	FY 93
Synthesis and Processing	286.0	251.6	232.1
Theory, Modeling, and Simulation	74.6	68.5	71.3
Materials Characterization	144.6	127.8	127.8
Total*	505.2	447.9	431.2

Excludes funding for classified research and education/human resources.

3.2.3 Department of Energy

Most of the nonclassified materials R&D is conducted by the Offices of Energy Efficiency and Renewable Energy, Energy Research, and Nuclear Energy. DOE's materials program encompasses a broad range of studies, from fundamental research to large-scale development of energy technologies. The R&D programs are carried out primarily by the DOE national laboratories. Projects include the development of high-temperature materials to improve operating efficiency of energy system; and processes for waste minimization,

Table 3.3. DOE AMPP R&D funding by research component (dollars in millions)⁶²

AMPP Component	FY 91	FY 92	FY 93
Synthesis and Processing	148.1	163.8	192.1
Theory, Modeling, and Simulation	38.4	40.9	46.9
Materials Characterization	174.2	175.1	184.3
Total*	360.7	379.8	423.3

Excludes funding for education/human resources and national user facilities/other

recycling, and resource recovery. A detailed listing of DOE's materials projects is provided in the Annual Report of the Energy Materials Coordinating Committee (EMaCC).

3.2.4 National Aeronautics and Space Administration

NASA's materials R&D supports aeronautics and space applications. Aeronautics research emphasizes advanced materials that will improve the performance, durability, economy, and environmental compatibility of civil and military aircraft. As a result of evolving materials and structures requirements, NASA increasingly has emphasized advanced metals and polymer matrix composites for airframe structures, and high-temperature polymeric, intermetallic, and ceramic matrix composites for subsonic and supersonic turbine engines. Space research focuses on synthesis and development of space-durable materials. Areas of special interest include development of carbon-carbon composites, ceramics, and ceramic matrix composites for lightweight thermal protection systems, and advanced metallic alloys, metal matrix composites, and polymer matrix composites for lightweight cryogenic tanks. The NASA Advanced Composites Technology Program (ACT) is one of the major national programs aimed at advanced composites for airframes, and the Lightweight Materials Program will interface with this effort to determine joint development areas and program progress that may relate to automotive goals.

Table 3.4. NASA AMPP R&D funding by research component (dollars in millions)⁶²

AMPP Component	FY 91	FY 92	FY 93
Synthesis and Processing	46.0	49.8	60.2
Theory, Modeling, and Simulation	33.1	35.6	44.6
Materials Characterization	32.7	34.0	42.4
Total*	111.8	119.4	147.2

*Excludes funding for education/human resources.

3.2.5 National Science Foundation

The National Science Foundation (NSF) supports basic and applied research to promote the synthesis of advanced materials; enhance fundamental understanding of the physics and chemistry of materials; promote further understanding of the links between synthesis or processing and the structure, properties, and performance of advanced materials; and promote development of novel processing and manufacturing methods that result in functional materials with novel or superior properties. NSF recently launched a 5-year plan to enhance research in synthesis and processing of new materials. Activity is increasing in several areas, including mathematical and computer modeling and net-shape processing.

Table 3.5. NSF AMPP R&D funding by research component (dollars in millions)⁶²

Component	FY 91	FY 92	FY 93
Synthesis and Processing	83.3	104.0	134.7
Theory, Modeling, and Simulation	53.0	55.8	64.0
Materials Characterization	70.9	73.5	79.4
Total*	207.2	233.3	278.1

*Excludes funding for education/human resources and national user facilities/other.

3.2.6 Other Programs

Several workshops addressing issues related to the Lightweight Materials Program have been organized. As part of the program planning effort for the program, the DOE Office of Transportation Materials (OTM) sponsored a needs assessment workshop on Materials for Lightweight Vehicles in mid-June 1992. This workshop and the resulting program plan were developed for OTM by the Oak Ridge National Laboratory. The workshop was attended by automotive material suppliers, automotive companies, and DOE's national laboratories. The results of that workshop were provided to all participants and are the basis for the technical plan contained in this document. In early September 1992, a workshop on computational simulation of materials processing and performance for automotive applications was held in Detroit. This workshop was sponsored by OTM and coordinated by Los Alamos National Laboratory, its results are incorporated into the Lightweight Materials Program Plan, and the summary is included as Appendix E. OTM also sponsored a workshop, coordinated by Pacific Northwest Laboratory, on automotive coatings exclusive of paint. Results of this activity proved to be less applicable to the area of lightweight materials. However, applicable information has been included in this multi-year program plan, and the workshop summary is included in Appendix F.

Tentatively scheduled for Clearwater, Florida in May, 1993 is a DOE workshop on high rate deformation processes and aluminum product applications in transportation. The workshop will be sponsored by DOE's Office of Transportation Materials and coordinated by the American Society of Mechanical Engineers.

New and expanded DOE projects which relate to the Lightweight Materials Program include:

Synthesis and Processing

- Synthesis and Processing of Materials for Corrosive Environments
- Advanced Techniques for Near Net Shape Processing of Bulk Ceramics
- Advanced Techniques for Processing - Welding and Joining
- Synthesis and Processing of Structural Polymers
- Basic Research on Tribological Studies
- High Temperature Load Bearing Structural Ceramic Matrix Composites
- Ceramic Manufacturing

Theory, Modeling and Simulation

- Synthesis and Processing: Modeling and Computation
- Basic Research on Tribological Studies
- High Temperature Load Bearing Structural Ceramic Matrix Composites
- Ceramic Manufacturing

Materials Characterization

- Advanced Techniques for Processing - Welding and Joining
- Synthesis and Processing of Structural Polymers
- Basic Research on Tribological Studies
- High Temperature Load Bearing Structural Ceramic Matrix Composites
- Ceramic Manufacturing

In discussions with industry on the needs for lightweight automobiles, several programs and activities were noted that are already contributing to their goals. These include several new work areas that are being negotiated for possible DOE Defense Program Technology Transfer Initiative CRADA funding, notably modeling for metals casting, modeling of plastics injection molding, improvement of structural reaction injection molding for composites, superplastic forming for metals and computing initiatives to enhance codes that relate to crash performance. In other DOE programs, several of the needs are being peripherally addressed, for example, Fossil Energy is sponsoring work on iron/aluminum alloys which are of interest for automotive exhaust systems. New activity on technology transfer is developing through DOE's Energy Research Program, some of which may impact materials R&D needs identified here. Also, the major new initiative, ARPA (Advanced Research Projects Agency) coordinated dual use Defense Technology Conversion, Reinvestment, and Transition Assistance Program, will undoubtedly substantially impact the automotive industry.

3.3 THE FEDERAL ROLE FOR NATIONAL COMPETITIVENESS

An effective program to develop materials for lighter weight automotive components requires a well-planned, well-coordinated industry and government effort with a multi-year funding commitment. Because many of the materials being examined represent new technology made possible by an ever evolving understanding of material behavior, industry suppliers and automotive manufacturers view the technology development process to be moderately risky. Moreover, it is clear that long-term development of many materials and their processing techniques will be required before they are ready for incorporation into the automotive marketplace. Although research by industry suppliers, automakers, universities, and government laboratories is encouraging, it has not yet progressed to the point that supporting structures, engine components, and other high weight components are being replaced by lighter weight materials in the average mid-size automobile. Automakers are unwilling to commit to alternative materials and processing techniques until a sound technology base is in place. At the present time, most automotive suppliers are too small and have too little capital to perform the R&D without the assurance of near-term business success. Similarly, the international automotive marketplace is such an intensely competitive environment that U.S. automakers do not have the capital funds to invest in R&D that may not yield a return for many years. While industry is willing to share costs on certain parts of this project, a government commitment to stable long-term funding will accelerate

development of the technology and bolster the competitiveness of our nation's largest industry.

It is important that the activities conducted under the Lightweight Materials Program be coordinated and complementary with those of other private and federally funded programs. The government, by actively coordinating these activities and ensuring an effective relationship with other private and federally funded programs, can realize the most cost-effective and efficient development of lightweight materials for incorporation into passenger vehicles.

In summary, the factors supporting a strong federal role in the development of Lightweight Materials for Automotive Applications include the following:

- The long-term nature of the research.
- The widespread potential applicability of these materials across many major U.S. industries.
- The strong positive national economic, energy, and environmental implications.
- Retaining a strong competitive position of the U.S. automotive industry in the world marketplace.
- The need for coordinated federal and private sector efforts to meet fuel efficiency requirements.
- The positive impact of upgrading existing automotive structures to lighter systems that support and are mandatory for platforms such as electric and hybrid vehicles. This is certainly enabling technology for any "Clean Car" of the future.

4. TECHNICAL PLAN

The Lightweight Materials Program focuses on the development of materials and primary processing methods for the fabrication of lighter weight components which can be incorporated into automotive transportation systems. Military or aerospace applications will not be addressed. The technical agenda, to be executed jointly by industry, government laboratories, and universities, provides a logical progression from material and process feasibility studies to determination of scalability and manufacturability necessary to develop cost-effective, reliable, environmentally friendly, and safe processing techniques. The level of automotive weight reduction, reliability and processing improvement will be determined by the testing of materials and components representative of specific industrial applications. R&D activities are organized into a work breakdown structure with five major elements: applications assessment; supporting technologies; environmental, safety, and health; materials and process development; and manufacturability.

4.1 IMPLEMENTATION STRATEGY

The technical program focuses on the long-term, enabling R&D priorities identified by industry to be the key to the development of materials for producing lighter weight automobiles. For this program to be successful and result in greater competitiveness for the U.S. automotive industry, domestic manufacturers must have a premier role in executing the technical agenda. Consequently, all elements of the program will be closely coordinated with industry. In many cases, the American automotive industry will conduct the R&D activities. Process feasibility demonstrations, process engineering, component fabrication, and component testing activities will be conducted mainly in industrial laboratories using existing industry facilities and technical expertise. Industry facilities for simulated and in-service testing of components representative of specific applications will be used to provide feedback on the level of improvements achieved and to define areas of deficiency where additional developmental activities are required. Subsequent to these component tests, material demonstrations will be used to assess scalability, manufacturability and production economies. Government laboratories will provide support to industry in the areas of material design and process modeling, material characterization, fabrication, data base generation, recycle technologies, and test method determination.

4.2 TECHNICAL APPROACH

The overall approach to the Lightweight Materials Program is illustrated in the flow charts provided in Figures 4.1–4.6. In addition to illustrating the major work elements and their interactions, the flow charts provide examples of specific material types, vehicles systems, manufacturing technologies, and material performance categories to be investigated during the program.

The approach provides a logical progression in the development of materials and fabrication technologies for lighter weight vehicles, starting with the required material attributes and moving in a sequential manner through the specific vehicle subsystems,

Fig. 4.1. Overall program activity flow chart

Fig. 4.2. Required systems attributes

Fig. 4.3. Vehicular systems for materials applications

Fig. 4.4. Property performance requirements

Fig. 4.5. Candidate vehicular materials

Fig. 4.6. Material and component fabrication

performance requirements, material characterization, component fabrication, and final field testing. Because the applicability of the fabrication methods given in Figure 4.6 depends on the specific material system to be processed, the service environment, the component it is being used in, and the economic requirements of the application, a number of potential processing techniques will be included in the feasibility studies. The specific techniques to be studied will be selected based on industry assessments of the potential to provide cost-effective components for specific applications. Only the most promising techniques, which are demonstrated at laboratory scale as part of these studies, will be carried forward for continued development. The selection of materials will include application routes for near-, mid-, and long-term uses. Continued development in fabrication engineering will emphasize the conversion of laboratory processes into ones suitable for the preparation of cost-effective, reliable components of ever greater complexity. Fabrication and testing of representative components will be used by industry to demonstrate the level of improvement achieved and the readiness of the process for pilot-scale demonstration. Pilot-scale operation of component manufacturing processes, along with industrial input, will be used to project cost and performance at commercial scale.

The materials selection, test method development, fabrication prototyping, material testing, and performance evaluation will be carried out by teams from American automakers, American automotive suppliers, the various automotive material consortiums, universities, and government laboratories. These teams will provide the comprehensive approach necessary for success of the program.

4.3 TECHNICAL TASKS AND WORK BREAKDOWN STRUCTURE

The tasks required to meet industry's needs in developing materials and processing methods for making lighter weight automotive components have been organized into the work breakdown structure shown in Figure 4.7. In addition to the principal technical elements of Materials and Process Development; Environmental, Safety and Health (ES&H); Supporting Technology; and Manufacturability; a Systems Requirements element has been included. This element provides for the detailed technical assessment of industry requirements and the analyses of the most promising material systems and processing techniques to be developed for specific applications. The elements will be integrated by an overall program planning activity. A summary description of the technical needs and goals of research included under each element is provided below. Appendix A contains charts detailing the research needs identified to date by interaction with the automotive industry. The charts are presented in accordance with their subgroup (i.e., steel, aluminum, etc.) priority ranking. A more detailed version of the work breakdown structure is provided in Appendix B.

4.3.1 System Requirements

The System Requirements element contains five subelements that together identify and define the industry needs for material technology, potential applications for materials, material performance requirements, cost-benefit analysis (including material cost targets/drivers), and industry specific issues. The application assessment subelement defines the various opportunities for vehicle weight reduction by the use of alternative materials. This includes

determining the potential impact of using alternative materials on fuel efficiency, crashworthiness, manufacturing methods, and associated costs. The materials requirements subelement examines the specific material performance goals for the incorporation of alternative materials into various automotive components. It examines not only the impact of changing materials on the final consumer product but also the impact to industry in terms of design changes, manufacturing method changes, and process improvements.

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Fig. 4.7. Work breakdown structure of Lightweight Materials Program

The technology needs subelement addresses the technology and R&D needs to enable meeting material requirements for selected applications. This subelement is used to establish the research direction and select development areas and teams best suited to address defined priorities. The life-cycle cost analysis subelement will examine the benefit/cost to both the consumer and industry of using lightweight materials. It will focus on industry costs such as retooling, processing time, processing manpower, raw material, assembly time, scrap generation, and recycling. It will also consider consumer costs such as reliability, repairability, and fuel conservation. In addition, this subelement will establish national cost benefits such as industrial competitiveness, fuel use reduction, and value-added job generation. The institutional issues subelement will survey the industry specific benefits and drawbacks of changing to alternative materials. It will consider the impact on the existing supplier base, the vehicle redesign efforts necessary, the issues of worker retraining and consumer perceptions. It will include impacts of ES&H issues, insurance and liability issues, and will address infrastructure needs.

4.3.2 Supporting Technology

The Supporting Technology element includes the more basic or generic support tasks of material design, materials R&D, durability evaluation, material systems modeling, and ways of incorporating these materials into newly designed automotive components. These provide the scientific foundation for successful material design, fabrication, and incorporation. While the nature and level of supporting technology activities will depend on the material systems and manufacturing techniques under investigation, they will generally focus on the areas described below.

Material design addresses both the design of alternative materials and designing components with alternative materials. The activities will focus on the development of models which predict the properties and useful lifetime of various materials for comparison with specific applications requirements. The activities will also provide an integrated product design framework which predicts the material properties and processing routes that will best meet the requirements of a given application. These objectives dictate three related activities which are defined as the materials R&D subelement. First, micromechanical representations of alternative materials must be developed from which the overall properties of the material can be predicted from the behavior and interactions of microscopic constituents—fiber, matrix, grains, dislocation, interfaces, etc., depending on the material. Second, micromechanical failure modeling is needed to understand probable failure modes and methods of each material as it relates to micro-level events. Finally, macromechanical models are needed to define the overall response of the component to the thermal, environmental, and mechanical loadings of specific applications. This will give designers a database from which to make material selections. For some of the materials this type of analysis already exists, but for other materials there is very little usable design data available.

To understand the lifetime performance characteristics of alternative automotive materials and to support the development of the primary processing routes, a thorough characterization of the properties of the materials under extended use conditions is necessary. The durability evaluation research activities are focused on obtaining this information. The principal research tasks include determining the effects of extended use in various service environments including chemical variations, temperature fluctuations, vibratory loading, and cyclic use stressing. Identifying and characterizing the response of automotive materials under these conditions will provide the property data base which is necessary to model material behavior and to give designers the critical understanding essential for using these materials. Accelerated testing and modeling necessary to predict in-service performance will be included to address the needs of new and emerging materials. This will facilitate their use and application to vehicles without the delay associated with long-term testing and characterization.

With the incorporation of new materials into the available automotive material design base will come changes in the ways that automobiles or their components are designed. The innovative structures subelement will consider ways of maximizing the benefits of each alternative material by designing parts in different ways. It will take advantage of alternative processing methods, parts consolidation, part size reduction, and design method changes and will focus on increasing reliability and efficiency by minimizing the negative properties of each material while maximizing the positive properties. This subelement will build on the

fundamentals that are developed in the previous subelements.

The computational analysis subelement will support the previous elements with regard to materials modeling fundamental to understanding performance and behavior in anticipated applications. This element will concentrate primarily on modeling of materials, with the separate computational modeling subelement under Materials and Process Development concentrating on process modeling.

4.3.3 Environmental, Safety, and Health Technology

The Environmental, Safety, and Health Technology element is designed to evaluate environmental issues such as recycling and waste minimization, as well as safety and health issues. It also examines the abilities of alternative materials to meet the environmental and safety standards of industry, government, and consumers. The ability to recycle waste, created during the production of automotive components and after the useful life of a component, is key to the incorporation of any automotive material into vehicle systems. The recycling subelement will focus on technologies for the recycling of waste, generated in the production process, back into the production process and into lower demand consumer products. It will also consider ways of recycling automotive components after their useful life is completed. Closely related to the recycling technology is the area of waste minimization. The goal of this subelement is to reduce the amount of nonrecyclable waste that is generated during the production process. It is also essential to reduce the amount of nonrecyclable waste that is present in automobiles after their useful life. This subelement will not only concentrate on minimizing total system waste but also on technologies for handling the non-recyclable waste. Areas of emphasis will include a determination of the total environmental impact of introducing new materials and ways of reducing negative environmental effects.

Passenger safety is of primary concern to customers and manufacturers. Designers require a complete understanding of material responses in various crash scenarios before being able to confidently incorporate alternate materials into automotive designs. The crash modeling subelement will concentrate on understanding and modeling material behavior in collisions. A wide spectrum of tools will be employed including computational modeling, static testing, dynamic testing, and life-cycle dependent design information. Closely related to crash modeling is the subelement of energy dissipation. It is critical to develop an understanding of how well a new material absorbs energy that may be induced by a variety of collision scenarios. New materials should progressively crumple and thus absorb the kinetic energy dissipated during a crash. This is critical to improving passenger safety by reducing the energy imparted to passengers in automotive crashes. This subelement will be studied using computational modeling and dynamic testing, resulting in design usable models and data.

Automobiles are required to meet a vast array of government, industry, and consumer standards related to improving safety and reducing environmental impacts. The standards and certification subelement will be used to evaluate materials based on their potential for meeting these standards. Focus will concentrate on the impact new materials will have on both the individual automotive components and the total vehicle system.

Toxic substances can be created during the production of automobiles, during the use

of automobiles, in the recycling of automotive materials, and during the decay of nonrecyclable automotive components. The toxicity subelement will seek to reduce or eliminate the presence and release of toxic materials throughout the life of automotive components. This function must be performed during the evaluation of new materials to minimize negative impacts on people and the environment.

4.3.4 Materials and Process Development

The Materials and Process Development activities focus on materials selection, process engineering, and component fabrication and testing. The fourth task, joining, responds to the need for methods to attach various materials to similar and dissimilar materials in order to fabricate complex parts or incorporate components into overall systems.

Materials selection determines the potential of a candidate material to meet specific application goals that are required for various systems in an automobile. The work in this phase will be at laboratory scale, using simple geometries. Research tasks will address mechanical properties, fatigue properties, chemical properties, long-term reliability, potential recyclability, and potential ease of fabrication. Mechanical property analysis will include the determinations of tensile strength, compressive strength, fracture toughness, response to a variety of temperatures, bending strength, and other characteristics found necessary for a given application. The analysis of fatigue properties will include creep and fatigue testing for materials in various environments and temperature ranges. The chemical property determination will seek to evaluate the response of potential materials to environmental factors, including sun baking and a variety of automotive fuels and fluids. Analysis of long-term reliability will be used to determine the effects of aging and prolonged exposure to salts, fuels, and fluids and to predict material responses to these environments. Recyclability issues will be paramount in the selection of any material, including reuse of production generated scrap, recycling post-use automotive components and disposing of nonrecyclable waste. Materials selection will be conducted by using available data or by the characterization and evaluation of simple material samples, using testing and modeling methods developed under Supporting Technology's tasks.

Process engineering focuses on the development work necessary to convert laboratory processes to ones suitable for the manufacture of representative components exhibiting required properties and economics. These activities include process modeling, the establishment of processing-property relationships, and materials and microstructure optimization. The major activity is the development of the relationships among processing parameters, microstructure, and properties. Experimental evaluation of the effects of processing parameters such as time, temperature, speed, and environment will be conducted to determine their relationship to the fabricated material and, thus, its manifestation of properties on potential automotive components. Processing properties will be varied to determine their effects on resultant material properties. Performance will be determined by thermal, mechanical, and environmental compatibility tests on simple geometries. Process models will be developed to support and guide the experimental activities.

Component fabrication and testing activities will be conducted to demonstrate the ability to process component geometries representative of specific application and to test these

components in simulated and in-service environments. The results of these tests will be used to measure progress and to identify areas where additional process development activities are required. Component fabrication will focus on geometries representative of the most promising potential applications for each type of material. Component evaluation activities will follow these to establish the interrelationships among component processing methods, performance responses, and associated properties. The impact of processing variables on the materials, test coupons, and component parts will be determined. The component evaluation tasks will include detailed characterization of the material in its component geometry and the physical, thermal, mechanical, and chemical properties of the specific as-processed materials.

Joining studies will focus on methods of attaching each alternative automotive material to itself, to polymers, to metals, and to various composites. It will also include design for disassembly and the methods of detaching materials and components. The work will include welding, adhesive, and mechanical attachment techniques. The long-term properties of joints will also be investigated. Joints formed by various methods will be evaluated not only for simple joints but also for multiple joints involving multiple parts, complex joints used under complex loading conditions, and composite joints formed by a combination of joining techniques. The microstructural impact (if any) of the attachment method will be examined. The effects of the joining method on the physical, mechanical, and structural properties of the materials and joints will be determined. Methods of conducting NDE of joints in a manufacturing environment will be an essential element for the incorporation of new materials into the automotive industry or any other industry.

Computational modeling will focus on process modeling required to allow optimization of materials, processes, and components. This activity is anticipated to be applicable across all the above tasks and will have a significant impact on the ability of the automotive industry to implement new materials. It will address models for predictive capabilities in process parameters, component and tool design, and part performance. It should directly impact the capability to minimize cost and material waste and maximize part quality.

4.3.5 Manufacturability

Manufacturing crosscuts all activities and will focus and guide R&D in the other areas. The six parts of this task are flexible manufacturing, economic analysis, engineering designs, scaling methodology, process control, and waste management. Flexible manufacturing will seek ways to increase the field of manufacturing methods to generate parts. Economic analyses include studies of manufacturing costs as a function of yield and part-production rates, as well as projections of economy of scale and related cost benefits realized through high-volume production and movement up the manufacturing learning curve. Engineering design assessments will establish property and performance targets for components fabricated in a manufacturing environment and the probability of success in achieving these in large-scale production. Scaling methodologies will focus on the design, fabrication, and operation of pilot-scale facilities. Design studies will identify the minimum size unit operations for an economic manufacturing process. Pilot-scale facilities will be used to verify economic and performance projections and to achieve optimization of process control by identifying bottlenecks or problems associated with commercial-scale automotive production of alternate materials. Pilot-scale facilities will also serve as test beds for evaluating NDE techniques,

joining methods, and recycling technologies and for developing the statistical process control procedures necessary to achieve performance, cost, and reliability goals. For each material, these activities conclude with a demonstration of the capability to reliably fabricate automotive components from lighter weight materials. At this point, process development activities are considered complete and subsequent scale-up and commercialization can be conducted.

4.3.6 Management, Planning, and Support

This task element encompasses all activities necessary to provide overall Lightweight Materials program planning, monitoring, integration, and oversight. Work conducted under this element will include development of solicitations, selection of research projects, monitoring of research in place, coordination with activities of other federal programs, analysis of issues related to both technical and managerial aspects of the program, and scheduled reviews with industry.

4.4 PROGRAM SCHEDULES AND MILESTONES

The general federal budget and authorization cycles are shown in Fig. 4.8. This indicates the overall planning, budgeting, and execution schedule demands and includes the top-level milestones for the Lightweight Materials Program. A more technical presentation covering the anticipated first 5 years of the program is provided in Figure 4.9, recognizing that the budget authority is not defined for the FY 1994-1997 years. The implementation milestones reflect the anticipated timing for issuing requests for proposals and awarding contracts to accomplish priority activities of the work breakdown structure. The remaining milestones indicate the expected progress in each area consistent with the resource requirements discussed in Sect. 6.

The management plan, described in Sect. 5, provides for periodic reviews of progress and direction. These reviews will result in updating of the multi-year program plan and milestones.

Fig. 4.8. Planning, budgeting and execution schedule

Lightweight Materials Work Breakdown	Program Year				
	Year 1	Year 2	Year 3	Year 4	Year 5
System Requirements Application Assessment Materials Requirements Technology Needs Lifecycle Cost Analysis Institutional Issues					
Supporting Technology Materials Systems Design Materials R&D Durability Evaluation Innovative Structures Computational Analysis					
ES&H Technology Recycling Waste Minimization Crash Modeling Energy Dissipation Standards and Certification Toxicity					
Material/Process Development Materials Selection Process Engineering Component Fab/Testing Joining Technology Computational Modeling					
Manufacturability Flexible Manufacturing Economic Analysis Engineering Design Scaling Methodology Process Control					

Fig. 4.9. Lightweight Materials Program milestone chart

5. MANAGEMENT PLAN

5.1 MANAGEMENT STRATEGY, IMPLEMENTATION, AND CONTROL

The DOE—OTM, under the Deputy Assistant Secretary for Transportation Technologies, Energy Efficiency and Renewable Energy, is responsible for overall management of the Lightweight Materials Program. The DOE-OTM is responsible for establishing program goals and objectives, implementation policies, and funding levels. It is also responsible for coordination with other federal agencies and DOE offices. Management efforts will focus on two primary areas: first, successful development of the LWM technology through the efficient use of public funds; and second, ensuring LWM technology contributes to U.S. international competitiveness. In accordance with DOE policy of decentralizing project management to field and laboratory sites with established capabilities, DOE-OTM is assigning responsibility for the day-to-day management of the LWM Program to the Oak Ridge Field Office (DOE-OR) as the principle field office, and to ORNL as the lead national laboratory. The project management responsibilities of ORNL include technical project planning, implementation, and control. ORNL will also be responsible for coordinating the technical efforts with related activities in other federal agencies such as NASA, DoD, DOC, etc. DOE-OTM will ensure consistency with, and integrate programmatic efforts to meet the goals of Congress and the Administration especially as reflected in national priorities under the Energy Policy Act of 1992 and the Clinton-Gore "Clean Car" Initiative.

To achieve the goals of the program, the majority of activities will be accomplished by the U.S. automotive industry, including material and component suppliers. Because the LWM technology and its development could have a significant effect on the international competitiveness of U.S. industry, the program will be managed such that the technology

Fig. 5.1. Overview of DOE-OTM, DOE-OR, and ORNL organizational interfaces

results of funded R&D accrue only to those industrial companies able to protect LWM developed technology from transfer to foreign competitors. Contracts, grants or cooperative agreements will be awarded to industrial firms, U.S. industry consortia, universities, and other appropriate organizations.

The DOE-OTM, DOE-OR, and ORNL organizational interfaces are shown in Fig. 5.1. The formal program direction and budget guidances are provided to DOE-OR by OTM through program guidance letters. DOE will contract, as necessary, for technical consulting and program oversight support. Required support may be sought from DOE's national laboratories, professional societies, national academies, and other appropriate organizations.

5.2 MANAGEMENT RESPONSIBILITIES

Within DOE, the responsibility for management of this program is assigned to the Conservation and Renewable Energy's Deputy Assistant Secretary for Transportation Technologies—Office of Transportation Materials. Managerial responsibilities for DOE-OTM, DOE-OR, and ORNL within the Program include the following, which will be addressed by the management plan to be prepared by ORNL.

- Overall program management and direction, including development and revisions to planning documents.
- Analyses and assessments to identify and benchmark both domestic and foreign capabilities and applications.
- Initiation and oversight of all foreign interfaces, contacts, or relationships relevant to the Program.
- Coordination and liaison with R&D programs of other elements within DOE and other government agencies, and execution of memoranda of understanding as necessary.
- Analyses and recommendations to the Assistant Secretary, Conservation and Renewable Energy, regarding program requirements, issues resolution, and management.
- Coordination with domestic industries, user industry, related industry associations, and other entities outside DOE to obtain recommendations and viewpoints on program implementation and to coordinate related federal and private sector activities.
- Participation in the annual federal budget process to obtain appropriations and obligation of appropriated funds.
- Organizing and monitoring of technical oversight and management panels.
- Decisions on funding of research and development projects, after receiving input

from program participants.

- Establishment of ongoing review mechanisms.
- Selection of contractors, financial assistance recipients, and consultants.
- Ensuring coordination and integration of work done by industry, government laboratories, and universities.
- Preparing statements of work and contractor selection criteria.

5.3 INDUSTRY PARTICIPATION

Involvement of private industry is an essential element of the program. Private industry is expected to take a leadership role in the development of research proposals and in providing guidance on program scope and direction. The automotive industry consortia under the leadership of the U.S. Council for Automotive Research (USCAR), especially the newly formed U.S. Automotive Materials Partnership (USAMP) and including the Automotive Composites Consortium (ACC), the Auto-Steel Partnership, and the Vehicle Recycling Partnership, will be relied on for their guidance and input to necessary technologies and R&D direction. Additionally, national industry associations are expected to have a role in coordination and review of program activities. Through their relations with the various industries either participating or benefiting from the developed technology, industry associations can further the progress of the program by participating in peer review groups, supporting government-industry dialogue, and promoting successful technology transfer.

5.4 INTELLECTUAL PROPERTY

It is the intent of DOE to ensure domestic control over the technology which results from the LWM Program so as to improve the economic competitiveness of U.S. industry. Negotiations on intellectual property rights on R&D projects will be based on the cost-share percentage that the industrial participants provide.

5.5 REPORTING AND TECHNOLOGY TRANSFER

The management controls for this program include financial and technical progress reports and periodic program reviews and coordination meetings. Bimonthly management reports will provide technical highlights and details of the financial, procurement, and milestone status of all in-house and subcontract work. Semi-annual technical progress reports, topical reports, and open literature publications on appropriate work will be issued.

Technology transfer efforts in the program will also include workshops, annual reviews, and presentation of particular program results at selected national industry meetings and government reviews.

6. RESOURCE PLAN

Recommended financing has been developed for the Lightweight Materials Program based on input of industry partners and reasonable and consistent cost share anticipated. In the "recommended" option shown, the federal funding required to execute the FY 1995 through FY 1999 phase of the program is \$230 million for technical labor, and approximately \$16 million for research facilities and equipment. Projected industry cost sharing of \$195 million for labor and \$7 million for equipment augments the federal funding and is necessary to achieve the program's objectives.

6.1 COST AND FUNDING

The funding and number of personnel required to execute the first 5 years of the recommended program are shown on a year-by-year basis in Table 6.1. For all options, the cost projections are based on the estimated total number of research personnel needed to execute each element of the work breakdown structure. Funding requirements are given in constant 1993 dollars and assume an average person-year cost of all participants of \$200,000 for research labor, overhead, and materials. The partitioning of the total LWM Program costs between industry and the federal government is based on projected industry cost sharing. Since the primary focus of applications assessments is the determination and reevaluation of the automotive industries needs, equivalent government/industry participation is assumed. Ten percent industry cost sharing is included in the supporting technologies tasks executed by government laboratories. Projected cost sharing is increased to 40% for the materials and process development activities as well as the scalability and manufacturability activities. Beyond the first 3 years of the LWM Program, cost sharing would increase to at least 50%. The elements of process development, recycle and manufacturability become increasingly more prominent as the program develops.

The recommended option, with a total 5-year federal funding requirement of \$230 million and industry cost sharing of \$195 million, encompasses the development of the primary approaches to lightweight material fabrication. Staffing of each process option is consistent with industry suggested levels but will be flexible in program execution due to the need to implement materials and process developments in production systems. Process feasibility demonstrations are completed in the first 3 years, allowing early component fabrication and in-service testing. These tasks are critical to both the rapid adoption of lightweight materials by industrial end-users and the continuous refocusing of the program to the remaining development needs.

6.2 RESEARCH FACILITIES AND EQUIPMENT

Although extensive research facilities and sophisticated analytical equipment will be required to implement the program, some of these facilities already exist in industry and government laboratories. Industry has invested in the past several years to upgrade material processing capability, including laboratory-scale equipment for processing lightweight materials. In addition, emphasis on advanced materials in the last decade has resulted in a

variety of new facilities at government laboratories for the microanalysis, testing, and processing of these materials. These facilities are available and will be used to support this program. Expected advances produced by the program for both materials and process technologies will necessarily result in the requirement for bench and pilot scale process equipment, as well as specific and dedicated test equipment. Industry has expressed the need for central user facilities that could be capitalized to allow joint development work on a variety of materials and processes, which could be co-funded by the government, automobile companies, materials suppliers, and component suppliers. These facilities could benefit a wide cross-section of the manufacturing industry, as well as supports needs of government programs.

The estimated total cost over the first 5 years of the LWM Program for the equipment needs of the supporting technologies, materials and process development, and scalability and manufacturability elements is \$23 million. Based on a projected industry cost sharing of \$7 million of the capital expenditures in the materials and process development and scalability and manufacturability elements, the federal funding for research facilities and equipment is \$16 million.

Table 6.1. Resource requirements for the recommended option of the LWM Program

Work element	Program Year				
	FY95	FY96	FY97	FY98	FY99
	Research and technical support (person-years)				
Management, planning, and support	10	15	15	20	20
1. System requirements	15	25	30	30	25
2. Supporting technologies	45	60	85	80	70
3. E.S.&H. technology	20	30	45	45	40
4. Materials and process development	90	125	160	165	160
5. Manufacturability	70	90	115	120	145
Total person-years	250	345	450	460	460
Total estimated cost (\$MM/y)	55	75	95	100	100
Federal funding (\$MM/y)	35	45	50	50	50
Projected industry cost sharing (\$MM/y)	20	30	45	50	50
Total cost (\$MM):					425
Total federal cost (\$MM):					230
Total industry cost share (\$MM):					195

APPENDIX A

EXPANDED RESEARCH NEEDS

The contents of Appendix A reflect the results of an industry workshop held in Dearborn, Michigan in June of 1992. A summary of information gathered during industry visits representing a technical needs assessment of the automotive industry were presented to the audience. Breakout groups then reviewed, commented and reworked these to reflect opinions of a broad cross-section of industry sitting "around the table" as opposed to being in private meetings. Attempts were then made to define high priority focus areas within each technology and their benefits, success criteria and need dates.

WORKSHOP SUMMARY REPORTS - STEEL RESEARCH NEEDS

- Reasons:** Near-term opportunity for weight reduction
Estimates of 4-10% reduction possible
Small cost penalty
Low risk associated with implementation
- Primary needs:** Improved formability
Improved quality control and materials consistency
- Needs:** Process modeling, development, and optimization
- Castings process improvement
 - Optimized performance/weight of components
 - Quality improvement
 - Material recovery efficiency
 - Stamping process knowledge
 - Handle material consistency issues
 - Component optimization
 - Cost optimization
 - Hydroforming process development
 - Improved joining techniques
 - Welding
 - Adhesive bonding

STEEL SUBGROUP RESEARCH PRIORITY REPORT

RESEARCH NEED: ADHESIVE BONDING OF HIGH STRENGTH STEELS

Research Goal: Develop a reliable adhesive system for bonding bare and coated high strength steel to itself and/or to other materials.
Potential Benefits: Elimination of weld associated material property degradation. Improved joint efficiencies. Facilitates the use of dissimilar materials.
Success Criteria: Reliable adhesive system.
Need Timeframe: 3 years
Priority Ranking: 1

RESEARCH NEED: ADVANCED PROCESSING OF STEEL COMPONENTS

Research Goal: Identify and develop new ways to fabricate components out of high strength steels. (Super plastic forming, fluid forming, explosive forming, hot forming, spray forming, etc.)
Potential Benefits: The ability to use higher strength steels. (Weight reduction, safety)
Success Criteria: Prototype parts and processes.
Need Timeframe: 1-7 years
Priority Ranking: 2

RESEARCH NEED: MACHINING METHODS FOR HIGH STRENGTH CAST STEEL AND CAST IRON

Research Goal: Improve the machinability and machining methods for high strength cast steels and cast irons.
Potential Benefits: Reduced weight by making thinner components.
Success Criteria: Demonstration of production processes.
Need Timeframe: 3-6 years
Priority Ranking: 3

RESEARCH NEED: WELDING OF THIN GAUGE HIGH STRENGTH STEELS

Research Goal: Investigate and minimize material property degradation associated with all types of welding.
Potential Benefits: Improved reliability, performance, and safety.
Success Criteria: Reduce material property degradation.
Need Timeframe: 2 years
Priority Ranking: 4

RESEARCH NEED: PROCESS MODELING FOR IMPROVED HIGH STRENGTH STEEL CONSISTENCY

Research Goal: Identify and model critical steel processing steps such as hot rolling, annealing, steel making, etc.
Potential Benefits: Improved high strength steel consistency resulting in thinner gauge components.
Success Criteria: Improved consistency.
Need Timeframe: 5 years
Priority Ranking: 5

WORKSHOP SUMMARY REPORTS - ALUMINUM RESEARCH NEEDS

- Reasons:** Significant near-term opportunity
Competition with foreign automakers
Ease of material implementation
- Primary needs:** Improved formability of sheet products
Low-cost, high-reliability joining techniques
Casting development for powertrain applications
- Needs:** Aluminum materials and processing
- Stamping processes
 - Material handling to minimize labor
 - Thick section forming
 - Surface treatment to minimize defects
 - Casting processes
 - Process modeling for optimized properties and material use
 - Rapid prototypes representative of components
 - Materials and processes for wear components
 - Other processes
 - Low-cost alloys
 - High-rate, low-cost superplastic forming
 - Welding, adhesion bonding, and crimping
 - Surface treatment for corrosion, joining and finishing
 - Repair techniques
 - Low-cost sheet aluminum fabrication

ALUMINUM SUBGROUP RESEARCH PRIORITY REPORTS

RESEARCH NEED: IMPROVED FORMABILITY OF SHEET PRODUCTS (2-5 mm for Structural and ~1 mm for Panels)

Research Goal: Improved alloy design - composition, TMT, etc.
Modify stamping process to allow aluminum forming with existing equipment (sensors control); modeling

Potential Benefits: Reducing manufacturing costs - improve quality of end product

Success Criteria: Manufacturing cost same as for steel

Need Timeframe: Alloy design - stamping: ~5 years

Priority Ranking: 1

RESEARCH NEED: CASTINGS

Research Goal: Improved wear resistance (alloys - coating surface treatments) not liners.
(Try to use existing facilities)
Achieve uniform consistent quality castings through modeling and process control interactions.

Need Timeframe: Biggest impact for \$ is next 5 years - largest effect on weight.

Priority Ranking: 2

RESEARCH NEED: JOINING TECHNIQUES FOR WROUGHT AL ALLOYS

Research Goal: Evaluation of various joining techniques - mechanical, weld, adhesive, etc.

Potential Benefits: Improved performance and reliability of joints (fatigue, corrosion, durability)

Priority Ranking: 3

RESEARCH NEED: CHARACTERIZATION OF PROPERTIES OF EXISTING COMMERCIAL ALLOYS AND JOINTS

Research Goal: Provide data base for engineers

Priority Ranking: 4

WORKSHOP SUMMARY REPORTS - MAGNESIUM RESEARCH NEEDS

- Reasons: Excellent potential for weight reduction
 Good replacement for plastic in certain applications
- Primary needs: Casting modeling
 Improved elevated temperature properties
 Expanded supplier base
 Reduced piece cost
- Needs:
 - Casting models and process development
 - Geometry, mechanical performance, and cost optimization
 - Net-shape processing
 - Prototypes with in-service performance characteristics
 - Elevated temperature properties
 - Improvement in creep and strength
 - Alloy development
 - Joining Systems
 - Eliminate galvanic corrosion
 - Low-cost components
 - Expanded cast component supplier base
 - Optimized quality and material recovery
 - Material supply base to meet large demand

MAGNESIUM SUBGROUP RESEARCH PRIORITY REPORTS

RESEARCH NEED: ENHANCED CASTING PROCESSES

Research Goal: Develop next generation molten metal handling/delivery technology
Potential Benefits: Reduced non-metallic inclusions
Reduced gas
Improved fatigue properties
Success Criteria: Achieve reliable castings at a cost competitive with aluminum alloys on a per volume basis.
Establish measurement methods for nmi.
Need Timeframe: 3-5 years

RESEARCH NEED: SURFACE TREATMENTS AND COATINGS

Research Goal: Provide surfaces with enhanced corrosion, wear, and adhesion properties.
Potential Benefits: Expanded use for exposed applications
Improved durability
Reduced assembly costs via adhesives
Success Criteria: Achieves corrosion properties of aluminum alloy 356
Need Timeframe: 3-5 years

RESEARCH NEED: IMPROVED LOW-COST CASTABLE ALLOYS

Research Goal: Create new generation of alloys with improved high temperature creep properties, higher ductility, and/or improved fatigue properties.
Potential Benefits: Create expanded opportunity for engine components.
Success Criteria: Achieve properties of competing aluminum alloys at a cost competitive with the aluminum alloys on a per volume basis.
Need Timeframe: 3-5 years

RESEARCH NEED: MECHANICAL PROPERTIES DATA

Research Goal: Provide mechanical property data base for existing and developmental alloys.
Potential Benefits: Establish design criteria
Success Criteria: Certified data base for the two major alloy systems.
Need Timeframe: 1-2 years

WORKSHOP SUMMARY REPORTS - OTHER METALS RESEARCH NEEDS

Reasons: Target weight reductions to allow increase in drivetrain efficiency
Complement gross weight reduction
MMC show high potential in structural components

Primary needs: Magnesium MMC materials development
Low-cost fabrication methods
Joining technology
Volume production methods

Needs:

- Metal Matrix Composites
 - Design and analysis of systems, microstructural behavior
 - Net-shape processing methods
 - High-volume production
 - Modeling of forming processes
 - Joining process technology
 - Improved high-temperature performance
 - Development of component/material supply base
 - Recycle technology development
 - Thin section processing
- Titanium
 - Improved wear
 - Free-machining alloy development
 - Lower cost components
- Aluminides
 - Net-shape processing methods
 - High-volume production
 - Joining process technology

OTHER METALS SUBGROUP RESEARCH PRIORITY REPORTS

RESEARCH NEED: AL and MG MMC PROPERTY DATA BASE

Research Goal: Development of structure-property data base for MMCs (including thermal fatigue, strength, microstructure stability, wear, etc.)
Priority Ranking: 1

RESEARCH NEED: AL AND MG MMC DEVELOPMENT

Research Goal: Development of cost-effective, high-volume, environmentally responsible, near net-shape processing technology for particulate reinforced MMCs, including machinability technology modeling and joining
Priority Ranking: 2

RESEARCH NEED: AL AND MG MMC DEVELOPMENT

Research Goal: Development of cost-effective, high-volume, environmentally responsible near net-shape processing technology for fiber-reinforced MMCs, including machinability technology, modeling, and joining.
Priority Ranking: 3

RESEARCH NEED: DEVELOPMENT OF TITANIUM ALUMINIDE COMPONENTS

Research Goal: Development titanium aluminide components employing high-volume, net-shape production technology.
Priority Ranking: 4

RESEARCH NEED: DEVELOPMENT OF LOW COST TITANIUM COMPONENTS

Research Goal: Development of lower cost titanium components including development of improved machinability technology.
Priority Ranking: 5

WORKSHOP SUMMARY REPORTS—UNREINFORCED POLYMERS RESEARCH NEEDS

Reasons: Very low potential weight
 Potential for low-cost systems
 Easier recycle than reinforced systems

Primary needs: High stiffness and strength
 Economic recycle capability
 Part and process optimization
 Higher temperature capability

Needs:

- Resin development
 - Higher stiffness and strength
 - Liquid Crystal Polymer (LCP) and other self-reinforcing systems
 - Economically recyclable resins
 - Higher temperature resin systems
 - Low-cost, high-performance resins
- Process development
 - Modeling of all processes
 - Optimized component design, performance, and material use
 - Improved process control
 - LCP processing for controlled properties
 - Tooling improvements for increased quality/lower cost
- Applications development
 - Prototypes that indicate in-service performance
 - Accelerated testing for aging and durability
 - Prediction of long-term mechanical performance

UNREINFORCED POLYMERS SUBGROUP RESEARCH PRIORITY REPORTS

RESEARCH NEED: SHORT TERM NEEDS

Research Goal: Upgrade properties of commodity plastics such as polypropylene, abs and san, nylons
Potential Benefits: Where the improved properties can permit replacement for metals. Improvement in impact resistance, hdt, and mechanical strength
Success Criteria: Significant improvement in target properties.
Need Timeframe: 1-3 years

RESEARCH NEED: MEDIUM TERM

Research Goals: Conductive materials through additives and chemistry.
Low permeation polymer systems, process multilayer technology
Polymeric foam technology
Reliability and long term life prediction
Large part multilayer processing technology
Improve process and product modeling
Potential Benefits: Paintability (avoidance of primers) - electrostatic dischargability and battery applications.
Design freedom
Noise abatement
Processing confidence to reduce long lead time in introducing improvements (reduce recalls).
Across wall thickness-tailored properties
Long term reliability
Success Criteria: Weight Reduction
Weight reduction, useful with alternate fuel systems
Need Timeframe: 4-7 years

RESEARCH NEED: LONG TERM

Research Goal: Liquid crystal polymers of improved processability and physical properties (including compressive strength) increase isotropicity.
Potential Benefits: High strength, lightweight, adaptable to current paint bake technology and low permeability.
Need Timeframe: 7-15 years

WORKSHOP SUMMARY REPORTS—REINFORCED POLYMERS RESEARCH NEEDS

- Reasons: Highest potential weight savings
 Useful for major structural components
 Seen as long-range future of ultra-light automobiles
 Design versatility for low-volume niche vehicles
- Primary needs: Production rate processing technology
 Design methodology
 Low-cost materials and components
 Recycle technology
- Needs: • Production rate process technology
 - Statistically controlled processes
 - Modeling of fabrication processes
 - New process development for rapid forming
 - Under one minute cycle times (production run averages)
 - NDE, quality by process control
- Low-cost materials and components
 - Intermediate modulus carbon fibers
 - Rapid fiber preform technology (automated)
 - Low-cost, high-performance resins
 - Expanded supplier base for large quantities
- Recycle technology
 - Separation of mixed waste (fluff/plastics)
 - Recovery of constituents
 - Recovery of energy content
 - Design for disassembly
 - Consistency of materials between suppliers
- Lifetime issues
 - Repair technology
 - Durability, fatigue/environment
 - Joints/bonding durability

REINFORCED POLYMERS SUBGROUP RESEARCH PRIORITY REPORTS

RESEARCH NEED: LIGHTWEIGHT STRUCTURAL COMPONENTS

Research Goal: Develop manufacturing processes that demonstrate statistical process capabilities
Potential Benefits: Reduced weight - improved fuel economy
Less scrap
Success criteria: Low cost
Reproducibility
Low cycle time
Need Timeframe: 5 years
Priority Ranking: 1

RESEARCH NEED: MANUFACTURING OF CONSISTENT QUALITY PREFORMS

Research Goal: Develop techniques and understanding of preform technology
Potential Benefits: Improve consistency
Improved quality
Reduced scrap
Reduced cycle time
Success Criteria: Reduced variability
Reduced cost
Predictive capabilities produced
Need Timeframe: 5 years
Priority Ranking: 2

RESEARCH NEED: TECHNOLOGY FOR RECYCLING REINFORCED POLYMERS

Research Goal: Demonstrate commercial viability of recycling technology
Potential Benefits: Reduce environmental impact
Success Criteria: Commercial applications containing reinforced polymers
Need Timeframe: 10 years
Priority Ranking: 3

WORKSHOP SUMMARY REPORTS—COMPOSITES MODELING RESEARCH NEEDS

- Reasons: Allow expanded use of composites
 Handle major structural components design
 Address issues in liability
- Primary needs: Predictive capability for crash performance
 Rapid exercising of vehicle analysis models
 Database for structural/nonstructural materials
- Needs: • Crash energy management
 - Predictably and reliably absorb impact energy
 - Knowledge of degree of damage, residual performance
 - Performance models that duplicate in-service behavior
- Design with composites
 - Database for materials properties
 - Techniques/processing for rapidly building models
 - Parallel processing code development
 - Accelerated testing for long-term performance factors
 - Design models that account for production processes

DESIGN MODELING SUBGROUP RESEARCH PRIORITY REPORTS

RESEARCH NEED: RAPID EXERCISING OF VEHICLE ANALYSIS MODELS

Research Goals: Automatic mesh generation
CAD - FEM modeling
Constituent level modeling
Potential Benefits: Reduction in lead time
More efficient design (allows for reiteration)
Cost
Success Criteria: Composite model development time = current steel model development time
Need Timeframe: 1-3 years
Priority Ranking: 1

RESEARCH NEED: MATERIAL DATA BASE

Research Goal: Develop performance measures
Anisotropic constitutive equations
Test specimen geometries and procedures
Potential Benefits: Risk reduction
Improved predictive capability
Micro-mechanical modeling
Need Timeframe: 1-3 years
Priority Ranking: 2

RESEARCH NEED: PREDICTIVE CAPABILITY FOR PERFORMANCE

Research Goal: Code development (anisotropic material), static and dynamic analysis
Failure criteria
Improved joining techniques
Crash simulation
Potential Benefits: Design "confidence"
Smaller capital base
Durability
Cost
Need Timeframe: 3-5 years
Priority Ranking: 3

APPENDIX B
DETAILED WORK BREAKDOWN STRUCTURE

Fig. B.1. Work breakdown structure of Systems Requirements.

Fig. B.2. Work breakdown structure of Supporting Technology.

Fig. B.3. Work breakdown structure of Environmental, Safety, and Health.

Fig. B.4. Work breakdown structure of Materials & Process Development.

Fig. B.5. Work breakdown structure of Manufacturability.

APPENDIX C
PUBLICATION REVIEW—MATERIALS TECHNOLOGY OVERVIEW

PUBLICATION REVIEW—MATERIALS TECHNOLOGY OVERVIEW

As the auto industry enters the twenty-first century, the look of cars and the methods and materials used to make them will change dramatically, creating opportunities for lightweight materials.¹¹ The requirements for improved fuel economy and reduced emissions are forcing automakers to decrease the weight of vehicles⁶, which can be accomplished by designing automobiles with lighter weight, high-strength materials. Ideal lightweight materials for automotive usage would have minimum mass, low raw material cost, low density, high modulus of elasticity, excellent dimensional stability over a wide range of temperatures, good vibration dampening characteristics, high flexural strength, high impact strength, low process and fabrication costs, excellent potential for recycling and good fabrication flexibility.¹²

Cost is the number one driver for an automaker to switch from a steel part to a part made from an alternate material and overall cost savings for switching may come more from the production method than from the material selection.⁷ U.S. automakers are expected to transition from 500,000 vehicles of a model per year to 50,000–100,000 vehicles of a model per year, with many more models available. This will require rapid and cost-effective retooling to remain competitive. The savings in tooling costs and quick design turn-around that can be achieved using alternate materials could outweigh the low cost of steel stamping material as model run volumes drop.¹¹

An obstacle to using alternate materials is the recyclability of some of the candidate materials. Scrap is a large part of the cost of producing automobiles because of both material costs and waste disposal costs.¹³ Methods to decrease scrap and increase recycle would give automakers a significant production cost advantage over their competition. Recyclability of automotive components after the automobile's useful life will grow in importance in coming years, and manufacturers of recyclable automotive components will be at a great advantage. It is important that designers engineer recyclability into automotive components. To do this, a vast array of information about alternate materials will be necessary. For many alternate materials, a sufficient engineering data base does not exist to aid designers in materials selection for recyclability. This problem will have to be addressed by large scale research efforts.¹¹

A vast array of materials are available for design of transportation systems including metals, plastics and composites. To switch to alternate lighter weight materials, there are several important design considerations, including part complexity and mechanical demands. Designing with composites and plastics can simplify assemblies. A designer can mold complex parts without machining while obtaining a lighter weight part. This eliminates the time and material waste associated with machining and assembly. Before designing a part, however, a designer needs a clear understanding of its importance for energy absorption, weight reduction, and mechanical integrity.¹⁷ Designing parts from alternative materials requires a new set of parameters from those used in designing steel parts.⁷ Those parameters need to be further defined so that a wider range of materials are available for designer consideration. Defining a material's usage parameters can only be met by basic materials research.

C.1 STEEL

Steel has long been the automotive material of choice because of good mechanical properties, fabricability, raw-material availability, good recyclability, favorable market price and the wealth of experience.⁴ Its properties such as strength, ductility, toughness, and corrosion

resistance can be engineered as needed for an enormous range of applications. New automotive steels include bake-hardenable steels, ultra-high-strength steels, interstitial free steels and micro-alloyed steels.¹⁸

Advances have been made in reducing vehicle weight by using steel. Lighter automobiles can utilize higher strength steels with higher fatigue strengths and improved stiffnesses that can be fabricated in thinner gauges. In addition, ease of formability is required. These properties can currently be provided by bake-hardenable steels.¹⁹ Since 1981, steel manufacturers have used easily formable soft steel that strengthens during the paint bake cycle. The resulting components can be made thinner, lighter, and easier, which results in parts that are economical to form yet have high dent resistance. Specific applications include automotive doors, hoods, trunk lids, and other areas requiring light weight and high stiffness.¹⁸

Micro-alloyed steels exhibit high yield strengths without heat treating. These steels can economically provide higher strengths and stiffnesses for crankshafts, ring gears, connecting rods, steering arms, and clutch hubs than conventional cast iron.¹⁸ Increasing the strength of these steels has yielded reductions in component weight by allowing the use of thinner sections. There is, however, often a price to be paid in the reduction of corrosion resistance by shifting to higher performance steels.

Potential increases in corporate average fuel economy (CAFE) standards will compel another round of vehicle weight reductions, which should stimulate new powder metallurgy applications. Ford currently uses approximately 360 different steel powder metallurgy parts worldwide, adding up to 42,000 tons per year. It is forecast that this number will increase by 20,000 tons in the years ahead.¹⁵ Nearly 60% of German-made powder metallurgy parts and 80% of Japanese parts are used in automobiles. Connecting rods are growing in powder metallurgy applications in Europe. BMW will install them in both automobile and motorcycle engines in 1992. Jaguar and Volvo should have hot forged steel powder metallurgy rods the following year. Both Ford and General Motors have powder metallurgy engine projects underway. Ford's new modular V-8 engine contains 15 pounds of powder metallurgy parts, including steel connecting rods. General Motors has also built a V-8 engine with powder metallurgy steel rods for 1992 production.¹⁶ Other examples of technology applications have shown cost reductions of up to 75% for throttle lever assemblies and camshaft weight savings of 30-40% due to near-net shape processing.^{21,22} Benefits also include use for highly stressed parts, elimination of heat treatment, and secondary machining while providing better control of dimensions and improved appearance.^{14,22} Steels produced by powder metallurgy suffer severe corrosion when in contact with methanol containing fuels. It is estimated that 20% of automobile engines produced by 1995 will need to be compatible with fuels containing methanol. Developing new alloys and improving the performance of existing ones will be essential for powder metallurgy to achieve its potential.¹⁶

Improving the corrosion resistance of steel sheet for automotive body panels, exhaust systems and fuel tanks has been the aim of a large amount of research.²³ Iron-based alloys containing 8% and 12% Chromium have been introduced for use in magnetic components that require more corrosion resistance, including fuel injectors, fuel pump motor laminations, and solenoids for antilock braking systems.²⁴ Most steel companies have developed coatings to improve corrosion resistance, including hot dip galvanizing, electro-galvanizing, zinc coating and Zinc-Nickel coating.¹⁸ There is increasing interest by automakers in using thermal barrier coatings on engine components that are subjected to high exhaust temperatures. Thermal barrier coatings offer advantages in keeping heat in the combustion zone to improve efficiency, reducing component surface temperature to provide protection from thermal shock

and oxidation, and controlling heat loss to temperature sensitive components. In addition, ceramic coatings can provide wear resistance, depending on the type of mechanical loading involved.²⁰

C.2 ALUMINUM

As vehicle weight reduction becomes more important in reducing fuel consumption and emissions and as long-term recyclability becomes a larger environmental concern, aluminum becomes more alluring for transportation applications. Potential weight reduction of automotive components by 25–45% is the primary advantage of aluminum; however, its recyclability and corrosion resistance are other major benefits. One significant problem with aluminum use has been in joining. Aluminum is especially sensitive to fatigue cracking in spot welds. To combat this problem, adhesives have been developed that reduce the need for welds.²⁵

Aluminum use in Mercedes-Benz vehicles is projected to go from 4% in 1986 to 6% in 1996, with the largest change being in the use of aluminum alloys to replace cast iron in crankcases.⁵ Jaguar's top-of-the-line sports car is almost entirely aluminum, including the engine, an adhesively bonded aluminum chassis, and the skin. Stainless steel clad aluminum bumper plates have been developed that offer a 32% weight reduction compared with chrome-plated steel, as well as improved corrosion resistance. Alumax uses aluminum forging to make parts that are lighter in weight than steel forgings and provide close tolerances while reducing machining by 95%. Specific parts include brakes, suspension systems, air conditioning compressors, turbocharger back plates, and engine parts such as rocker arms and pistons.²⁵ Toyota recently introduced forged aluminum alloy valve lifters in its 32-valve V8 engine. By reducing the weight of the valve train, valve spring loading was reduced, thus reducing the torque required to drive the camshaft and improving fuel economy. The 43% weight savings gained by the switch resulted in an overall 15% weight savings for the train, which translated to a fuel efficiency increase of 1.2%.²³

Most aluminum companies have chosen to use a space frame for automotive research (see Fig. C.1). The main benefit of aluminum space frame technology is weight savings compared to steel, but other advantages include parts consolidation, elimination of stamping presses and simplification of assembly.²⁵ An aluminum space frame has been made of less than 100 parts compared to at least 300 parts in a typical sheet steel body. This simplifies the assembly process requiring less labor and equipment and reducing the production costs. Another advantage is the ability to build individual body subassemblies that can be used on several different models.^{25,26} Aluminum space frames can reduce primary body structure by 35% or more and enhance stiffness-to-weight ratios, ride smoothness, and handling without adding bulk.²⁶ The result is manufacturing that is cost competitive and flexible in both volume and design requirements and a structure with the same or greater stiffness and crashworthiness as a steel vehicle that weighs much more.²⁵

Efforts to increase applications of aluminum in automobiles began to increase in 1991 and will continue as key drivers for the industry in the foreseeable future.²⁴ Aluminum alloys are widely used in engines because of their low density, corrosion resistance, and good forming and casting characteristics. A large weight reduction can be achieved by replacing cast iron engine blocks with either aluminum blocks having cast iron liners or with linerless, hyper-eutectic silicon aluminum engine blocks.²⁰ General Motor's Saturn uses a lost-foam casting process to produce many lightweight, high-quality aluminum parts, including engine

blocks, cylinder heads, crankshafts, and front cover heads.^{25,27} Work is underway to further upgrade aluminum pistons through the inclusion of reinforcing fiber inserts in regions subject to severe thermal and mechanical loads.²³ While many applications for aluminum have been found under the hood, only limited applications have been commercialized for structural components.

This rendering of a generic space frame illustrates the use of less than 100 aluminum extrusions and interconnecting aluminum die cast nodes which are robotically welded to form the car body. A limited number of aluminum sheet components (i.e. inner fenders, floor pans) are then attached to complete the body.

Fig. C.1, Automobile space frame concept. Photo courtesy of Aluminum Company of America (ALCOA).

Formability, corrosion resistance, joining, and surface issues have been barriers to structural applications for aluminum.²⁴ Automakers have expressed a desire to see aluminum alloys that may be superplastically formed into structural components. The advent of such alloys could potentially allow automakers to use a process that can significantly improve parts consolidation. Reliable joining methods for aluminum alloys could make them more attractive for structural use.²³

C.3 MAGNESIUM

Magnesium is another lightweight material used in the automotive industry. It compares favorably to aluminum, steel, and some plastics for certain applications. For example, compared with unreinforced injection molded plastics, magnesium die castings have strength/weight ratios up to 233% greater and stiffness/weight ratios up to 1150% greater.²³ Magnesium alloys are attractive to automakers concerned about crashworthiness because they fail in a ductile rather than brittle manner and provide an opportunity for major weight savings.²⁴

Dow Chemical reports that North America's automotive application of magnesium die castings has grown a compounded average of 35% per year over the past three years;²³ however, the average magnesium content of a U.S. built vehicle is only about 2 pounds, with the major use being in mounting brackets. Uses for magnesium alloys have been found in some larger components including valve covers, cylinder head covers, intake manifolds, rocker arm covers, air intake adapters, induction systems, clutch housings, four wheel drive transfer case housings, steering column shrouds, and specialized lightweight wheels.^{20,23} Magnesium alloys have been used by Chrysler to replace aluminum alloys as mounting brackets for alternators, power-steering pumps, air pumps, air conditioning compressors, and automatic tensioners resulting in a 33% part weight savings and improved vibration dampening characteristics. While magnesium is more expensive, cost benefits potentially arise from longer die life, higher casting rates, smaller die-casting machines, lower shipping costs, lower machining costs, and thinner components.¹⁹

Magnesium castings are attractive candidates for engine applications because they are lightweight and have good strength and stiffness at both room and elevated temperatures. Improvements in fuel efficiency could be achieved through reducing the weight of moving components in the engine by using magnesium alloys. Magnesium has a high damping capacity, as well as the thin-wall capability of the die casting process.²⁰ In addition, magnesium has a clear weight advantage over aluminum cast alloys.²³ Magnesium use, however, is limited because most magnesium alloys have a tendency to corrode making them suitable for only specialized applications. Current research shows promise for reducing corrosion of magnesium by the use of magnesium-lithium alloys.⁵ Corrosion could also be prevented by the appropriate coating technology or the development of new magnesium alloys.

C.4 TITANIUM

Titanium has typically been used in the aerospace industry but has been excluded from the automobile industry because of its poor formability at lower temperatures and the high cost of titanium alloys. A Japanese company has announced the development of a titanium alloy that is superplastically formable at lower temperatures. The alloy is already being used to make wrenches at a 35% weight savings over steel.²⁴

A U.S. company is developing titanium alloys which cost less than the typical Ti-6Al-4V alloy but are just as strong and more formable. The alloys are slated for auto engine parts including intake valves and connecting rods. The Japanese automaker, Honda, is particularly interested in this material, saying that they can achieve an additional 700 rpm by using the alloy while achieving 30% weight savings over steel. Additionally, the lower weight of the valve system permits the use of lower spring loads, which results in improved fuel efficiency

because of lower frictional losses. Titanium retainers are also showing greatly improved wear resistance compared with steel retainers, and Mitsubishi has specified titanium for this application. The only American use of these lower cost alloys is in making armored military vehicles.²⁴ Key factors to the growth of titanium in industrial applications are its resistance to corrosion, high strength, modulus, and low density.²⁴

C.5 INTERMETALLICS

Intermetallics offer the high strength at high temperatures, low density, high creep resistance, and high stiffness required for improved engine components. They are generally very hard and their strength increases with operating temperature, which makes them ideal for automotive engine parts. Advances in alloy design and processing technologies have improved their properties and have brought several intermetallics such as aluminides of titanium, nickel and iron to the brink of commercialization with beryllides and silicides still under development. The major draw back to intermetallics is their extreme brittleness with elongations often below 1%.²⁸ Alloying techniques for nickel aluminides have solved this, raising the elongation from essentially zero to as high as 53%.²⁸ Government and industry have been working together to establish fabrication processes such as melting, casting, forging, welding, and powder metallurgy techniques for nickel aluminides.

Titanium aluminides are under development as an engine material at General Electric Research Center and at Oak Ridge National Laboratory. Iron aluminides are of interest because their corrosion resistance and strength are superior to carbon steels. They show no oxidation at elevated temperatures or stress corrosion cracking in chloride environments.²⁸ To bring these materials to the automotive production line, research is needed in alloy development, characterization, and processability.

C.6 METAL-MATRIX COMPOSITES

MMCs are either in use or being prototyped for automobiles as structural members, engine parts, and wear surfaces.²⁹ The lightweight and high strength-to-weight ratio of MMCs could cut both fuel consumption and emissions. The lower inertia of composite engine parts reduces the internal work of the engine, resulting in higher engine speeds, more efficient combustion, and a reduction in emissions.³⁰ Some of the improved properties of MMCs increase as temperature rises, which is an added advantage in power and drivetrain applications.³¹ The addition of high-strength, high-modulus fibers improves the baseline matrix properties. A better understanding of property-microstructure relationships, however, is needed to explain the mechanisms of flow and fracture so that specific property targets can be met for a variety of applications.¹

Cast MMCs offer net or near-net shape parts, improved stiffness and strength and compatibility with conventional manufacturing techniques. In addition to providing products with low density and high strength and stiffness, this near-net shape technology offers cost savings by reducing the number of subassemblies, machining operations, and fasteners. Alcoa and Duralcan cast net-shape parts from aluminum-matrix composites such as automotive structural components for suspensions, brakes, and engines. The process produces good surface finishes and dimensional tolerances with quality levels equal to unreinforced aluminum while eliminating the need for machining and finishing.^{29,32} Squeeze casting of MMCs also offers high productivity and near-net shape formability. There is considerable variability in

the strength of composites produced by squeeze casting, and this remains a problem to be solved before the process becomes more widely used for the large scale manufacture of automotive parts.¹

Research into MMC pistons has yielded increases in engine operating efficiency and cuts in emissions. Aluminum-matrix composite pistons can be made lighter than aluminum pistons because the reinforcement increases high-temperature strength. In the early 1980's, Toyota made use of reinforced ceramic fiber aluminum alloy pistons for diesel engines.¹ Low-friction, lightweight MMC cylinder liners in conventionally cast blocks also have shown great promise for improving fuel efficiency and reducing engine block weight.³¹ Honda developed an aluminum block that incorporates cylinder liners made of alumina/graphite short-fiber reinforced aluminum. The block provides higher performance, is smaller, and weighs less than either cast iron blocks or aluminum blocks with iron liners. Other successful applications of aluminum MMC in automobiles include driveshafts and pistons.²⁰ Boron carbide in an aluminum matrix is being looked at by automakers for high-speed, high-friction environments such as reciprocating parts in engines. The material has low mass and high wear-resistance. By lowering the weight of moving parts, higher fuel efficiency could be achieved by reducing the internal work of the engine.³³

Powder metallurgy is being considered as a production method for MMCs in automotive applications due to its net shape production capabilities.²⁰ The relatively high cost of powder metallurgy composites is a limiting factor in many automotive applications.²³ Ford has stated that it has a great interest in MMCs, especially for rotating and moving parts. Because of the difficulty in machining MMCs, Ford is looking for net or near net shape manufacturing, including powder metallurgy to produce these advanced components.¹⁵

C.7 UNREINFORCED POLYMERS

A decade ago, conventional wisdom in the automotive industry held that it was only a matter of time before polymer-based materials replaced steel in most automotive applications. Their advantages were obvious: steel was heavy, expensive to tool, and subject to corrosion. Plastics were not.³ In 1989, Phillips Townsend Associates' research showed current plastics consumption in the North American auto industry was 22,750 tons per year. That number is expected to triple by 1994.^{3,34} Plastics are typically much weaker and more expensive than traditional materials.³⁵ They do, however, have natural advantages over steel. They are lighter by as much as 50%, offer better dent resistance, are more flexible, and stylistically they are highly desirable for dent prone vertical surfaces.³⁸ High energy levels are required to break current automotive plastics; however, when failure occurs, the fractures are brittle in nature.³⁶

Displacing the traditional materials used to produce automobiles requires that plastics compete cost effectively with less expensive materials.³⁵ The automotive trend is to target smaller market segments by producing more models at lower volumes. This change in production economics favors plastics which tend to be more cost effective at lower volumes due to their net shape manufacturability.³ Net shape plastic design eliminates the majority of separate parts and must be considered in overall program costs.³⁵ The total cost of a plastic part is influenced more by the amount of part integration than price per pound.³⁷ The knowledge base, however, for designing and manufacturing plastic products is relatively small compared with that for steel.³⁵

Plastics do have two major environmental drawbacks. They are a petroleum product and many are not easily recyclable.^{38,39} DuPont has reported that recycling options for thermoplastics are being extended through a new chemical depolymerization process, which it calls methanolysis.⁴⁰ Saturn says recyclability was a decisive consideration in the selection of thermoplastics for all exterior panels on the cars its firm introduced in 1990. BMW says that 80% of the 1992 325i model, by weight, will be recyclable. Japanese and European automakers have traditionally been heavy users of polypropylene, which is a recyclable material. Despite these advances in polymer recycling technology, most plastics are not recyclable.¹³ The recyclability of polymeric materials will require considerable research before wider use in the automotive industry becomes an environmentally friendly alternative.³⁸

Saturn Corporation is the first automaker to utilize, on a large scale, the technology that polymers offer. Front and rear fascias on Saturn cars are made of an elastomer which has excellent paintability, moldability, impact resistance, surface appearance and overall cost effectiveness. The material requires no primer or other special treatment prior to painting, but provides a finish superior to that of sheet metal. The elastomer parts are painted in-plant utilizing an environmentally friendly waterborne paint system. It can also be melt recycled, further improving its cost effectiveness. The ability to reclaim and reuse scrap was a key reason for selecting injection-molded thermoplastic for large exterior components at Saturn. Other benefits included design flexibility, corrosion resistance, impact strength, toughness, high durability and low material weight.³⁴

Polymers have a number of merits and demerits with regard to their potential use in automotive applications. Attractive characteristics are high design flexibility, manufacturing flexibility, and durability. Major disadvantages include brittleness, sensitivity to temperature fluctuations, and difficulty of attachment to other materials.¹² Using plastics can reduce metal stamping steps and componentry by more than 50%. It lowers retooling costs (plastic tooling averages about one-third the cost of steel tooling for the same part³), thus facilitating cosmetic design changes.³⁸ Research is needed into increasing ductility, reducing thermal expansion, improving joining methods, and increasing recyclability.

C.7.1 Low-Demand Applications

In the past few years, plastics have found increasing use in applications that do not place extremely high demands on the material. Automotive body panels represent the largest single area of plastics penetration. Plastic body panels have several advantages: plastic parts are corrosion resistant; they can reduce part weight by 30–40% for improved fuel economy; new models can be made by simply changing the design of the outer panels, resulting in cost savings for lower volume builds; curved surfaces that are difficult to form in steel sheet can be achieved in plastic panels because of their design flexibility; and the cost of changing molds for new plastic panel designs is only about one third that of dies for steel sheet forming.^{36,41}

A large problem with using plastics for external panels is expansion and contraction as they are exposed to high temperatures such as paint baking.⁴¹ Thermoplastics have much higher coefficients of thermal expansion than does steel, which causes processing problems when subjected to paint oven temperatures. A new way of coloring automotive components dispenses with the need for paint ovens, opening the way to much wider uses of plastics. The coloring method uses a dry-paint laminate and is slated for production on the exteriors of some 1993 General Motors and Ford cars. In addition, the new coloring procedures eliminate volatile organic compounds which reduce workplace hazards and environmental pollution.³⁸

Fenders are also a major penetration area for plastics.³ Front fenders for the Cadillac DeVille and Fleetwood are injection molded from polyphenylene oxide. The material provides the low warpage and heat resistance to withstand E-coat bake oven temperatures to 380°F.⁴² The cost of the tooling equipment for the Cadillac DeVille to produce one kind of injection-molded fender was \$600,000; the same part in steel would have required about \$2.3 million in tooling.³ Other areas of plastics penetration include the radiator grill for the GM heavy-duty truck. The new design reduced manufacturing costs by 10% and resulted in a lighter, more durable grill that was resistant to stress cracking and environmentally induced degradation.⁴³

C.7.2 High-Demand Applications

Plastics have found uses for certain high-demand areas which take advantage of their special properties. For components that contact methanol-containing fuels, plastics are the only materials capable of satisfying both the corrosive effects of methanol and the cost criteria.⁶ Corrosion of cast magnesium gear boxes has prompted some people to switch to a plastic alternative. The plastic gearbox is 20% lighter and allowed part count reduction from three to two.⁴⁴

Nylons have been developed which enable very tight tolerance molding of gears, cams, wear rings, and bearings. The largest use of nylon resins is for extrusion of fuel lines, fuel tank vent lines, air brake hoses, and compressed-air supply hoses. Great strides have been made in blow molding large parts out of nylon, such as automobile gas tanks, under hood radiator fluid reservoirs, and other complex hollowware.⁴⁵ The fuel-injected engines for Audi and Porsche feature nylon manifolds. The manifolds weigh 50% less and have smoother inside surfaces than the aluminum parts they replace.⁶

Under the hood applications for other thermoplastics include air out-take ducts for pickup trucks and clean-air intake ducts for turbocharged passenger cars. The ducts are blow molded and cost less than the wire-reinforced rubber parts they replace. A plastic-bodied, centrifugal, air-injection pump replaced a belt-driven pump housed in aluminum on the 1990 Corvette. It is resistant to high temperatures and corrosive chemicals and forms a gasketless seal with the aluminum mounting plate. It ensures more precise impeller clearances, thus aiding in more complete combustion of the gases in the catalytic converter. Other under-the-hood applications for high performance thermoplastics include air-filter housings, radiator end tanks, fuse covers, air ducts, distributor caps, and cooling fans.⁶

C.8 REINFORCED POLYMERS

The critical role of materials engineering in automobile design will be emphasized when federal regulations force new cars to travel farther on a tank of fuel while discharging lower levels of pollutants.⁶ The drive to reduce both cost and weight in automobiles has highlighted the need for manufacturers to develop processes for producing parts from fiber-reinforced plastics.³⁷ Although composite intensive automobile bodies are still the exception rather than the rule, there is no doubt of a global trend toward polymeric materials.³⁸ The result is a need for new materials as well as improved versions of more established materials.¹²

Auto systems of the future must weigh less than present cars and they must be less expensive to manufacture, run, and maintain. Advanced composites offer the potential to outperform steel in strength and stiffness at a lower total weight. They damp noise, integrate parts, corrode less, need less tooling and equipment, render class 'A' surfaces, can be recycled, need less maintenance, may be engineered to more varied specifications, and offer more design freedom. Advanced composites can be disassembled, shredded into short-fiber reinforced material and marketed as high quality engineering materials.⁴⁷ Aerodynamics and corrosion resistance are primary design considerations for automotive components in the 1990s and composites can meet these design considerations better than metals for many applications. Gloss and paint adhesion to composite substrates are two principal performance requirements for future composite materials.³⁰ The high cost of advanced composites has traditionally prevented their adoption by the automotive industry. Composites should, however, benefit from the analysis of total system costs, which reflect savings from part consolidation and reduced overhead.

Henry Ford demonstrated the impact resistance and durability of the first automotive composite by making a trunk lid of a soybean-based composite. The commercial application of composites has an extensive history in the marine, aerospace, and construction industries but has only evolved slowly in the automotive industry in the last 20 years.^{9,49} Composite use has been mostly limited to secondary structures and appearance panels but not to high load-bearing components.⁹ Composites allow both the materials and the vehicle to be engineered for optimum control of strength-to-weight ratio, stiffness, weight reduction, safety, and aerodynamics.¹⁷

Many applications for composites have been found in and out of the automotive industry. These applications have resulted in both weight savings and design simplification which have yielded cost reductions. General Motors has pioneered with such composite intensive models as the Fiero, APV vans, and the cars made by its Saturn subsidiary. Ferrari has opted for a side door air-grating, which will be compression molded of sheet molding compound (SMC) on its latest 348 model. As well as adding style, the 10 pound part weighs 7 pounds less than its steel equivalent, performs as well, and is corrosion resistant.³⁸ Various aerodynamic parts are being incorporated into automobile designs to reduce the drag coefficient as well as to satisfy the diverse tastes of the consumer. These parts include spoilers, roof deflectors, side skirts, mud guards, and wheel covers.⁴¹ The six most active areas of automotive composite development are exterior body panels, space frames, bumpers, driveshafts, suspension systems and instrument panels.³⁰

Polymer based composites have a number of merits and demerits with regard to their potential use in automobile applications. Attractive characteristics are high design flexibility, manufacturing flexibility, and durability. Major disadvantages include brittleness, sensitivity to temperature fluctuations, raw material cost, and difficulty of attachment to other materials.¹² Using composites reduces metal stamping steps and can cut componentry by more than 50%. It lowers retooling costs (plastic tooling averages about one-third the cost of steel tooling for the same part³), thus facilitating cosmetic design changes, and it saves up to 50% in weight.³⁸

C.8.1 Low-Demand Applications

In the past few years, composites have found increasing use in applications that do not place extremely high demands on the material. Automotive body panels are the largest single

area of composites penetration. Critical design considerations for the body panels are surface finish, heat sag resistance, coefficient of thermal expansion, designability, impact resistance, and modulus.³⁰ SMC is capable of providing as good or better Class A finish than steel and has demonstrated the ability to withstand E-coat bake temperatures. Weight savings with SMC over steel can be on the order of 20–30% and while steel retains a per part advantage in cost at high volumes, its higher tooling cost gives the edge to SMC in shorter runs.³ In medium volume runs, the price of the SMC panel is the same as for a sheet steel panel, with the advantages of a 20% reduction in weight and the capability of being molded as a single part without any joints.⁴¹

Although SMC is used sporadically in the European automobile industry, it has conquered a traditionally steel or aluminum application in bumpers. Audi, BMW, Mercedes, Peugeot, and Volkswagen now utilize SMC bumpers in their production vehicles. It is anticipated that the use of high-performance SMC will extend to other automotive structural applications as the industry gains experience in designing and working with the material.

SMC is a proven material for exterior body panels and is now being considered for engine components.⁶ Budd Company is making 30% glass fiber reinforced SMC engine parts, including valve covers and oil pans. The parts are lighter than steel stampings, less expensive than aluminum or magnesium die castings, dampen sound better than all three metals, and are more heat resistant than thermoplastic moldings.⁵¹ Detroit Diesel and Cummins Engine are replacing cast aluminum valve covers with SMC covers with advantages in reduced valve-train and other engine noise, reductions in machining by parts consolidation, and improved seal integrity due to better dimensional stability. Porsche plans to substitute SMC for aluminum in the oil pan for the engine of its 944 sports car citing weight and cost savings of 30%.⁶

Adequate ventilation systems, acceptable disposal methods, and in-plant and post-use recycling are key environmental problems facing automakers who use SMC. Diminishing landfill capacity makes it imperative that scrap SMC be recycled.³⁴ The technology for recycling SMC does not yet exist.

In addition to SMC there are a variety of other reinforced polymer composites either in use or as candidates for use by the automotive industry. An ultrasmooth, glass fiber reinforced polyester hood is made for medium-duty trucks by Freightliner. The plastic part has a finish that exceeds minimum requirements for a Class A surface. The weight of the one-piece hood is 84.5 pounds, which makes it 10–15% lighter than a similar SMC assembly. It has higher strength than SMC and lower tooling and fabrication costs.⁵²

Composites such as reinforced nylon are being designed into a number of engine applications which traditionally have used metal. Weight reduction is the primary driver in most metal replacement applications.⁶ Timing chain tensioners, bearing cages, transmission components, and sensors and valve covers are among the potential applications for high-performance nylons. German and Italian automakers are currently using reinforced nylon timing chain tensioners.⁵¹ A big three automaker has switched from die-cast aluminum to a compression-molded thermoset composite for valve covers on V6 engines. The composite cover provides a weight reduction of 0.3 kg while cutting total cost and damping vibration.⁶ Composites transmit 260% less noise at 1,000 rpm and 130% less noise at 3,000 rpm than die cast magnesium covers. Sound-damping valve covers made of glass-reinforced nylon can cost 5–25% less than comparable aluminum parts.⁵¹

The development of fusible-core injection molding has made possible the substitution of glass-reinforced nylon air-intake manifolds for parts made of cast aluminum. The result is a 50% weight reduction, better engine performance due to lower friction, and reduced total cost due to lower tooling costs. The 24-valve, six cylinder engine that powers the 1991 BMW 525 was the first commercial engine to use the composite air-intake manifold.⁵¹ BMW, Citroen, Peugeot, Renault and Ford now use composite air-intake manifolds produced by a variety of lost core molding techniques. The manifolds weigh as little as half of the same part made out of pressure-cast aluminum.³⁸

Increasing interest by the automotive industry is leading to further improvements in liquid molding of structural composites. Very large composite parts are now being prototyped using liquid preform molding processes.³⁷ Most liquid preform molded composites show tighter distributions in mechanical properties than low profile SMC. They also have higher tensile strengths and higher flexural strengths. On an equal part thickness comparison, preform liquid molding is generally slightly lower cost than SMC. Since it is also stronger, thinner parts can be used, which substantially lowers total part cost.⁵³

C.8.2 High-Demand Applications

Composites are beginning to find applications in automotive areas that require higher performance, such as transmission, universal joint, and other powertrain components.³⁰ Composite driveshafts offer reduced weight, design flexibility, and relative ease of fabrication. Critical rpm for composite driveshafts have averaged 17% higher than comparable steel or aluminum shafts due to their lighter weight.³¹ General Motors has the only major application of carbon-fiber to date, in a one-piece, composite truck driveshaft that replaced a heavier, two-piece steel assembly.⁴⁹ Introduced for pick-up trucks in 1980, composite driveshafts serve as proven prototypes for vans and passenger cars in the 1990s. The General Motors 1988 GMT-400 pick-up truck carries a composite driveshaft that is 60% lighter than the steel shaft it replaces, while requiring less torsional balancing. The composite version shows no temperature or environmental problems after road testing. Other drivetrain candidates are the axle and transmission housings.³⁰

A one-piece composite leaf spring weighing 8 pounds replaced an original steel spring consisting of seven pieces and weighing 41 pounds.³⁵ General Motors introduced filament-wound leaf springs in the 1982 Corvette, which are now being used on high-volume car and van programs.⁹ General Motors is currently using a glass/epoxy-composite leaf spring which out performs steel springs at one-third the weight.³⁰

Automakers have tested composite bumpers as one-for-one replacements for existing metal bumpers to save vehicle weight. The bumpers are simpler, perform as designed, and attachment parts are reduced.⁴¹ Front and rear bumper back-up bars made of 40% fiberglass-reinforced polypropylene were introduced on 1987 Ford and General Motors passenger car models.^{30,39} Composite bumpers have been in production for the Corvette in the Bowling Green, Kentucky, plant since 1989. Their introduction resulted in simplification of the bumper assembly process.⁵⁴

A wide range of other uses have been found for reinforced composites, with weight and cost savings being the primary drivers. The Budd Company in Troy, Michigan, has developed a composite structure brake drum that provides 30% better performance than conventional drums. Increased resistance to cracking and heat checking are additional benefits.⁵⁵ Vinyl

ester-fiberglass wheels have been under evaluation for more than 10 years and weigh about 50% less than stamped-steel wheels. Filament wound steering wheels using epoxy-fiberglass composites are under development for Audi models.³⁰ Polygon Company is prototyping a glass/epoxy strut for use by American automakers. BP Chemicals is developing carbon/carbon brakes for large trucks based on their potential for improving safety. Composites made with hollow glass microspheres can be used to save weight in structural automotive applications. The hollow microspheres are in a three-dimensional honeycomb formation and offer exceptional energy absorption, making it a natural for improving a car's crashworthiness.⁵⁶

Energy management is a major issue that must be addressed before composites can be more extensively used in automobiles. Vehicles must be capable of meeting stringent safety objectives, which places severe performance requirements on the structure. The use of composites in load bearing primary structures represents a significant challenge in this area. Many composites have been shown to be more efficient, per unit mass, in absorbing energy than metals in simple components under axial loading.^{5,48} Evidence is accumulating that fiber-reinforced composites can be efficient energy absorbing materials; however, research into understanding their behavior in automobile crashes and modeling that behavior with computer simulation is still lacking.⁴⁹

A fiber with great potential for automotive structural applications, on the basis of cost and performance, is E-glass fiber. In 1985, a Ford Escort front structure was prototyped with a molded E-glass fiber composite. Forty-two steel parts were replaced by one molded part, resulting in a 30% weight reduction and structural stiffness in excess of the steel structure.⁴⁹ Carbon fiber is also being investigated by some automakers. Carbon-fiber has been used to fabricate demonstration parts including engine blocks, engine brackets, suspension components, bumper beams, and bumper components. Austrian automakers have been filament winding demonstration driveshafts and bearings using carbon-fiber, and the Netherlands is researching the use of carbon-fiber leaf springs and bumper bars.⁴⁶

C.9 SANDWICH-STRUCTURE APPLICATIONS

Sandwich-structure composites are widely used in the aerospace industry. Work is currently underway to bring these composites into automotive production. Ford Motor Company has conducted a prototype program to develop a composite tailgate for the Sierra pick-up truck. The design selected and successfully demonstrated an integrated sandwich structure consisting of skins of preformed glass mat around a foam-plastic core, molded into one piece.³⁷ Buick and Oldsmobile tailgates are made from these composites and meet all design load and deflection criteria. The tailgate is two pieces and weighs 29.7 pounds. It replaces a seven-piece tailgate which weighed 42.9 pounds.⁹

Foam cores have been used in designing composite front-end structures. A modular automobile front end was prototyped and tested that consists of a polyurethane-foam energy absorber and support beam that replaced an assembly of 20 plastic and stamped-steel parts. The front end successfully passed the 5 mph pendulum and barrier tests and the 3 mph pendulum corner test while reducing vehicle weight by 28.5 pounds.³⁷ The composite front end was subjected to static crush tests with the result of no fractures in the composite. Dynamic barrier crash tests were conducted on the all-composite front end at 30 mph. The rails were crushed progressively and yielded good energy absorption. The dummy data met the federal requirements and the force levels showed that the composite front end structure can be crushed progressively proving the crashworthiness of the composite structure.⁴⁸ These

tests have given encouraging results, and it appears that with correct engineering and design synthesis, sandwich structures could be successfully utilized in vehicle energy management applications.

Race cars using composite chassis have been made with 30% greater torsional stiffness and a 25-30% weight reduction. Composites offer advantages in Indy cars, such as space optimization in the fuel cell area and ease of moldability for the complex contours in the lower chassis and underbody. Ford fielded a new Mustang race car in 1991 that reflects the chassis enhancements possible with composites. The chassis is made of a steel tube with interior panels of sandwich construction carbon-fiber/epoxy/honeycomb bonded to add torsional stiffness.¹⁷

Composites are beginning to make significant advances into mass-transit applications. European and Japanese manufacturers have taken the lead, putting advanced materials into commuter and intercity railway cars. The most extensive use of composites in mass-transit vehicles is in honey-comb panels for commuter and intercity railway cars. Advantages of using composites in subway vehicles include weight savings, increased passenger comfort (lower noise), and lower assembly cost. Weight savings yield faster acceleration and deceleration, reduce wear on bogies and track, reduce energy consumption, and lower overall operating costs per passenger mile. Assembly costs are lower because lighter parts can be installed quickly and easily.⁵⁷

The major application of composites in U.S. rail cars is the body shells for the Disney World monorail cars. Finished shells weigh an average of 1080 pounds—a 2000 pound reduction from the earlier aluminum cars. They offer advantages in thermal insulation, higher damage tolerance and longer maintenance intervals. The cars are capable of carrying 30% more passengers than their metal predecessors. A bus has been designed, using composites, that is only about half the 27,000 pound weight of U.S. buses. The bus exhibits little corrosion and the composite's light weight makes it possible to use a smaller engine and single, rather than twin, tires on the rear of bus. It cuts fuel consumption by 30%.⁵⁷

Future uses of composites in automotive applications will depend on total system economics.³⁰ Before composites are more widely applied, additional development work is required in addressing issues of durability, environmental effects, and joining. The area of manufacturing will require development to make these applications cost effective for the automotive industry.⁴⁸ Finally, there remains one central problem to the application of composites in most industries. Before composites can be more widely applied, it is essential to build a property database representative of the operating conditions to which the materials will be subjected.⁵⁸

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APPENDIX D. CONTRIBUTING ORGANIZATIONS

CONTRIBUTING ORGANIZATIONS

The following is a partial list of organizations that contributed information to this program plan. Many individuals provided input to us and helped us with discussions of ideas, goals, and direction for this effort. We are grateful and indebted to these participants and we apologize to any whose company may have been inadvertently omitted from this list. In many cases informal discussions were held with individuals and the following list is not intended to represent corporate endorsement of this program plan nor any commitment, implied or otherwise, to support the program by the listed organizations.

A. O. Smith
Aluminum Association
Alcoa
Allied-Signal
American Foundrymen's Society
American Iron and Steel Institute
Amoco
Arco Chemical
Argonne National Laboratory
Ashland
Automotive Composites Consortium
Auto-Steel Partnership
Brunswick
Budd Company
Caterpillar
Chrysler
Ciba-Geigy
CMI
Dana
Dow
DuPont
Duralcan
Eagle-Pitcher

Exxon
Ford
General Electric
General Motors
GenCorp
Hercules
Idaho National Engineering Laboratory
International Magnesium Association
Lanxide
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
LTV Steel
National Steel
Norsk Hydro Magnesium
Oak Ridge National Laboratory
Pacific Northwest Laboratory
Reynolds
Rockwell
Sandia National Laboratory
SMC Automotive Alliance
University of Michigan
Unique Solutions
U.S. Automotive Materials Partnership

APPENDIX E

SUMMARY OF WORKSHOP ON COMPUTATIONAL SIMULATION OF MATERIALS PROCESSING AND PERFORMANCE FOR AUTOMOTIVE APPLICATIONS

WORKSHOP ON COMPUTATIONAL SIMULATION

The following is a brief synopsis of results of a workshop held in September 1992 in Dearborn, Michigan for DOE, to provide input on Computational Simulation of Materials Processing and Performance. The results of this workshop have been generally included in the body of the report wherever possible, as a very major and critical R&D effort had been defined by all industrial participants as the need for materials performance models and also process models. This workshop re-emphasized the specific needs, and a complete report may be obtained from Dr. P. S. Follansbee of Los Alamos National Laboratory.

Three working groups were established to enable detailed technical interchanges and to generate prioritized lists of problems, examples and projects. The working groups were:

- Advanced materials processing
- Crashworthiness
- Machining, metal working, and casting

Several themes emerged from the plenary presentations and working group discussions. These included the following:

- The use of computational simulations could enhance the product design/manufacturing interface and reduce the product cycle time.
- Computational simulations could accelerate the introduction of lightweight materials through optimization of the manufacturing processes and through assessment of the integrated design/performance tradeoffs.
- There is a pervasive need for data, particularly for lightweight and composite materials, and for validated databases.
- An immediate opportunity exists to incorporate existing manufacturing simulation technologies, but, in general, extensive cross-cultural interactions will be required for meaningful advances.
- To be useful, and used, as a design tool, simulation technologies must be accessible by suppliers, be attractive to manufacturing engineers (rather than simply the R&D community), and provide "real time" feedback.

Specific recommendations include:

- Simulation tools for composite materials are required which can assist the designer in specifying manufacturing processes and in assessing the performance of these materials. These tools must be able to deal with the interfaces present as well as with the unique damage and failure mechanisms.
- For a small program, choose a correspondingly focused project, e.g. fluid flow processing of a metal matrix composite, the design of a reinforced thermoset or thermoplastic, the energy dissipation of a particular class of reinforced composite material, etc.
- For a large program, move from the component level to the integrated design/manufacturing process level.
- The need for databases should be considered a high priority, with a short term goal of providing data requested by the design engineers, and a long term goal of developing a better mechanistic understanding of how processing affects properties

and to incorporate this feedback into simulations.

- Simulation tools need to be made available to the transportation industry, with mechanisms for transmitting existing tools and updating as advances are made.

E.1 ADVANCED MATERIALS PROCESSING

This working group did not have a good depth of representation from the automotive industry, and tended to focus primarily on polymeric composites processing. Goals and R&D needs are consistent with those reported earlier, with emphasis placed on low-cost materials, damage assessment and crash modeling, and simulation and control of the manufacturing processes. Other themes included need to identify processing parameter effect on material and part properties, effects of the interface between resins and reinforcements, and cost and performance barriers. A review of the concurrent engineering approach to these materials indicated a need for a package capable of material, component and manufacturing process design. The design package would:

- Perform a preliminary structural analysis,
- Based on an in-depth database of material properties, manufacturing techniques, recycling aspects and economic considerations, select several candidate materials and the best manufacturing processes,
- Perform a manufacturing process simulation of the part for each of the materials selected.
- Using the output from the manufacturing simulation, predict what the properties of the actual component would be. This would include the actual fiber distribution, a spatial description of the voids, resin rich regions, etc.
- Perform an in-depth structural analysis of the final component.
- Iterate on this process until the optimum design/material/manufacturing process emerges.

Caveats include desiring a real time system, no extraordinary efforts on the designers part, and an expert system that learns from its history. A short/long term task breakdown was suggested.

the short term goals include incorporating existing available technology, designing individual packages as part of a modular system, improving material constitutive relationships to include process and environmental descriptors, and developing rough screening processes for material/process selections. Medium term goals could include extending manufacturing simulation tools to predict performance of fabricated components based on primitive material inputs. A long term goal may be to tie the packages together (drafting codes, structural analysis, processing and manufacturing simulation tools, and economic predictors) and automate the overall package.

E.2 CRASHWORTHINESS

The crashworthiness group discussed five topics in detail, three of which were directly applicable to the LWM Program and two showed partly applicable information. The topics and their activities are noted below :

- 1) General goals for analysis and simulation activities.
 - Enhanced vehicle safety
 - Energy conservation

- Development of light, inexpensive, energy absorbing composite materials
 - Deeper understanding of current design
 - Common language to facilitate discussion
- 2) Technologies of interest presented were:
- Preprocessing, as mesh generation is most intensive portion of analysis, current codes are limited, and automated algorithms are attractive to industry.
 - Analysis (see below)
 - Postprocessing, especially new visualization technologies.
- 3) Analysis Technologies - Materials
- General needs include improved mathematical models, predefined input parameters to characterize material, and validation data to characterize range of application.
 - Metals needs include rate dependent plasticity and damage and failure models, especially for aluminum alloys.
 - Composites needs include selections for optimum design and constituent properties, failure predictions and strength/energy absorption models.
 - Other needs related to lightweight material included models for honeycomb aluminum composites.
- Analysis Technologies - Finite Element Analysis
- Needs were noted in robust, contact algorithms, spot weld models, progressive damage models, enhanced element technology, bonding models and design optimization. These relate to lightweight vehicles through capability to optimize structures, however, tend to be at the periphery of a materials development program.
- 4) Related Applications
- Design-introduced failure modes for composites including edge effects in panels and design of failure triggers for enhanced/controlled energy absorption.
- 5) Possible DOE Action Items
- Development of material property database, including FEA model input parameters.
 - Develop benchmark test problem suite for quality assurance and validation of large scale analysis, especially on highly dynamic, nonlinear problems, including evaluation of material models.

E.3 MACHINING/METAL WORKING/CASTING

This group focused on manufacturing process simulation, with the following representing a summary of discussion points related to the Lightweight Materials Program.

- 1) Factors contributing to a decline in manufacturing excellence:
 - Product design/manufacturing interface has been overlooked.
 - Understanding of manufacturing processes has not increased in proportion to complexity of manufacturing processes.
 - Tendency to design to weakest part which leads to overdesign.
 - Fear of failure has discouraged innovative use of lightweight materials.
- 2) Rebuilding manufacturing excellence

- Use simulations to overcome shortage of manufacturing engineers and to improve manufacturing process understanding.
 - Use simulations to provide the needed design/manufacturing interface.
 - Enhance usage of lightweight materials through optimizing the processing of these materials and manufacturing with these materials using simulation technologies.
 - Objective should be to reduce product cycle times.
- 3) Component level needs in transportation industry
- Machinability as function of machine variables.
 - Quality of a casting.
 - Fluid flow processing of metal matrix composites.
 - Sheet metal formability and forming limit (especially aluminum).
 - Heat treatability as function of chemistry.
 - Microstructure/property prediction and control.
 - Wide material applicability/availability of databases.
 - Weldability (especially for advanced materials).
 - Databases on molten metals.
- 4) High priority requirements for manufacturing process simulation
- Do not limit to component level, extend simulations to assembly level.
 - A deep understanding of the manufacturing process must be developed.
 - Process simulations must be user friendly and give real-time feedback.
 - Tools must have general availability, particularly to suppliers.
 - Simulations must use process parameters that are easily understood.
- 5) Caveats and Concerns
- Must extend beyond R&D into manufacturing organizations.
 - Target suppliers as well as manufacturers, as suppliers have major process development responsibility.

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APPENDIX F

SUMMARY OF WORKSHOP RESULTS ON COATING FOR LIGHT MATERIALS

SUMMARY OF WORKSHOP RESULTS ON COATINGS FOR LIGHT MATERIALS

The following is a synopsis of results of a DOE sponsored workshop on coatings needs for the automotive industry, whose goal was to define where coatings could enhance the use of energy efficient lightweight materials. The complete workshop report is available through Dr. E. L. Courtwright of Pacific Northwest Laboratory. Four generic areas provided the workshop focus, these were 1) wear coatings, 2) hard protective coatings for plastics, 3) solar control coatings, and 4) process manufacturing issues. Paint issues were excluded since one other workshop in this area had been held.

F.1 WEAR COATINGS

Workshop discussions included reviews of wear mechanisms and solutions and needs for controlling these mechanisms under various wear processes. Needs for coatings were discussed along with failure mechanisms. The goal was to establish an understanding of needs and identify top R&D priorities. Coating technologies included thin-film deposition, such as chemical vapor deposition, plasma assisted vapor deposition, physical vapor deposition, ion plating, and ion beam assisted deposition. Factors involved in selection of processes included adherence, surface preparation, deposition conditions, and potential changes in physical properties.

Discussion topics in this area included use of expert systems and models for intelligently selecting coating materials, relationships between bench testing and engine performance, applications of functionally graded coatings and multilayer materials, and effects of coatings on recyclability of materials. Several research topics were identified, the primary ones relating to development of lightweight materials are listed below.

- Develop coatings for aluminum, magnesium, and metal matrix composites.
- Study compatibility of coatings with alternative fuels, including methanol.
- Coatings for extended life of aluminum stamping dies.
- Coatings for enhanced use of inexpensive dies for short production runs, e.g. injection molding.
- Study effects of coatings on recyclability and develop appropriate processing methods.

Several other research topics were identified and are available in the complete workshop report. Many of these areas would have an impact on weight savings, material usage, and/or quality of components in automobiles, but are not related as closely to the primary program goals of development of lightweight materials, hence are not summarized here.

F.2 HARD COATINGS FOR PLASTICS

Potential applications include engineering plastics for underhood components, such as valve covers, intake manifolds, etc., as well as reinforced and unreinforced plastics for interior trim, exterior trim and closure panels, and bumpers. Issues include mismatch in both elastic moduli and coefficients of thermal expansion, heat management due to low conductivity, and adhesion improvements. Certain coating types, such as ceramics, may have limited range of applicability due to property mismatches, and functionally graded materials may need to be developed. Industry trends for plastics coatings are toward surface appearance enhancement

for the vehicle life, with moves towards thermosets, two-component systems, and water base coatings. Goals are to increase scratch resistance, improve impact damage resistance, and allow application of lower cost plastics. Recyclability will be critically important for future plastics applications, and coatings could exacerbate this problem. Research needs include:

- Develop coatings to protect from environmental exposure (fluids, etc.)
- Develop high emittance/conductive coatings to allow control of heat in plastics.
- Study ion implantation of plastics with emphasis on economical approaches.
- Develop coatings that improve abrasion and enhance environmental protection of plastics.
- Develop coatings to enhance manufacturability and performance of beads, fibers and fillers in reinforced plastics.
- Develop coatings that will enhance impact resistance in plastic components.
- Develop coatings with graded interfaces to match properties of a variety of polymer compositions.

F.3 SOLAR CONTROL COATINGS

The workshop report, although focusing on the very significant and important R&D needs in this area, especially for electric and hybrid vehicles, did not relate development efforts to lightweight materials R&D needs. Indirect correlation can be made through use of solar control coatings to reduce air conditioner size and hence system weight. However, the real drivers for this technology come from power demand reduction. Solar control coatings will be referred to the electric and hybrid vehicle programs to address needs.

F.4 PROCESS MANUFACTURING ISSUES

Coatings for automotive uses could better be utilized if processing issues associated with cost, reliability, and scale-up could adequately be demonstrated. Examples include process areas from wear coatings and protective coatings for plastics previously mentioned. The coatings processes were categorized as follows:

Vapor Deposition	Chemical Vapor Deposition	Electro- Chemical	Spraying	Ion
Eb evaporation	Reactive gas	Aqueous	Detonation gun	Ion implantation
Thermal evaporation	Metal-organic	Molten salt	Electric arc	Ion beam assisted
Sputtering	Plasma enhanced/assisted	Electroless	Metallizing	
Ion plating	Laser assisted	Electrophoresis	Plasma	
Reactive sputtering	Microwave assisted		Flame-powder wire	

Various processes and process combinations are considered important for scale-up demonstration and pilot plant development. Especially noted were "Multisource Continuous Process Coatings System" where flexibility is built into a single process line, and one or more processes may be used in combination. Process models to allow optimization of coating materials and processes without the need for repeated process trials was cited as a major

need. The need for process and performance sensors was also highlighted. The following list of R&D areas was developed:

- Study manufacturability issues associated with earlier noted processes (e.g. light metals coatings).
- Study novel approaches that combine and utilize existing automotive databases and experience (e.g. magnesium coated with steel).
- Study prospects of surface strengthening of light metals and metal matrix composites.
- Perform scale-up demonstrations of promising new processes.
- Develop new and novel low-cost processes for high volume surfacing of materials.
- Develop modeling and control methodologies to improve reliability and repeatability of selected coating processes.

F.5 SUMMARY

The highest rated R&D needs from the coatings workshop are presented below.

- Develop coatings and coating technologies for magnesium, aluminum, and metal matrix composites.
- Develop coatings to protect plastics from automotive liquids and gasses, e.g. alcohol containing gasolines, antifreeze, and brake and transmission fluids.
- * Develop durable coatings for monolithic glass capable of reflecting 70% solar energy (35% or more reflection - 35% or less absorption).
- Develop coatings that will enhance the use of inexpensive dies for use in short production runs, e.g. injection molding of thermoplastics.
- Study coating techniques that will improve mar resistance, UV resistance, and moisture resistance of plastic materials
- Study manufacturability issues associated with coating light metals, e.g. aluminum, magnesium and metal matrix composites, with wear resistant materials.
- Develop coatings that improve abrasion resistance and enhance environmental protection of plastics, e.g. diamond-like/a-C:H.

* Not directly applicable to Lightweight Materials Program.

The number one need was identified as the development of coatings for lightweight metals. This was further emphasized by the highest rated processing issue, manufacturability concerns associated with coating light metals and metal matrix composites. This included the need to study coatings for the reinforcement materials to enhance processability and properties. In this area, issues involve adherence, difference in expansion coefficients, reactivity between matrix and reinforcements, and anisotropy of some composite materials.

Three of the top R&D needs related to protecting plastics, especially for appearance surfaces (abrasion and impact resistance) and environmental resistance (fluids, UV, etc.). The workshop results indicated that some focus had been placed on diamond-like coatings, providing economics and quality concerns can be achieved. Polymer coatings needs also included tooling coatings for wear resistance, focusing on economics and reliability issues.

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