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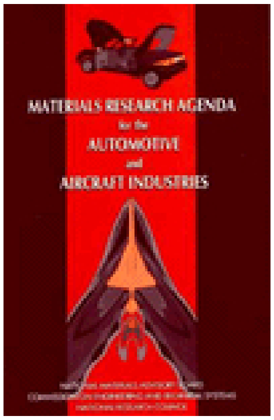

Materials Research Agenda for the Automobile and Aircraft Industries

Committee on Materials for the 21st Century,
Commission on Engineering and Technical Systems,
National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Materials Research Agenda for the Automotive and Aircraft Industries

Report of the
Committee on Materials for the 21st Century

National Materials Advisory Board
Commission on Engineering and Technical Systems
National Research Council

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1993

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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ABSTRACT

This study presents a materials research agenda for the commercial aircraft and automotive industries for the next two decades. Case studies from each of the industries are used as a basis for discussion within the report: the 50-mpg, 5-passenger sedan for the automobile industry and the high-speed civil transport for the aircraft industry. Although no case study could be selected that would cover all the important research issues in a field, these two examples were chosen because both were seen to be industry priorities dependent upon, in part, materials innovations. The conclusions and recommendations identify the general materials drivers for the industries over the next 10 to 20 years and the materials research required for each field.

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Preface

In 1989, the National Research Council (NRC) published *Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials*. This study addressed the status and future of materials science, the research opportunities, and the materials needs for several industries. The study concentrated on those areas of materials science and engineering that are traditional and ongoing and showed where additional research and changes in emphasis could lead to increased payoffs.

Based on this study, the National Science Foundation (NSF) requested that the National Materials Advisory Board convene the committee on Materials for the 21st Century to determine a more specific materials research agenda for the next 10–20 years for the commercial automotive and aircraft industries. NSF believed that a forward-looking study was needed to provide the materials-engineering research and development (R&D) community with an assessment of the future fundamental materials and manufacturing R&D required.

The statement of task approved by the NRC specified that a two-day workshop would be used to compile the information required on the environment in which these two industries currently operate and on the contents of the potential research agendas. The workshop was held on November 21–22, 1991. Experts involved in the materials-selection and R&D processes from both fields were invited. The attendees consisted of experts from the automobile and aircraft industries, representatives from affiliated materials-supply companies, materials scientists from academia, and representatives from government agencies and national laboratories.

To focus the workshop, a case study from each of the industries was selected for initial discussion. The committee selected two exemplary systems that should be of significance to the commercial aircraft and automotive industries for the next 10–20 years: the high-speed civil transport for the aircraft industry and energy-efficient vehicles for the automobile industry, specifically, the 50-mpg, 5-passenger sedan. Although the committee recognized that no case study could be selected that would cover all the important research issues in a field, the high-speed civil transport and the 50-mpg, 5-passenger sedan appeared to be the most generally applicable from a technology-driven perspective. The committee also limited the focus of the workshop to the major structural and mechanical aspects of these vehicles, realizing that the addition of such topics as working fluids and tire materials would require additional, topic-specific workshops.

The committee compiled the data from the workshop to ascertain the environment in which the two industries currently operate and then used this information to determine a materials research agenda for the next several decades. This report presents the results of these deliberations. Chapter 1 details the reasons for the selection of the case studies. The second chapter presents an overview of the environment in which the two industries operate and the general materials directions being pursued, based on the information compiled at the workshop. Chapters 3 and 4 discuss the future materials research required for the commercial automotive and aircraft industries respectively.

Bernard H. Kear,
Chairman

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Executive Summary

The goal of this study was to determine the materials research agenda for the commercial automotive and aircraft industries during the next two decades. These industries have important roles in the U.S. (and the world) economy: they employ over one million workers in direct and allied industries and their combined sales of $156 billion in 1991 made up roughly 3 percent of the gross national product for the United States.

The underlying issue in materials use in these two commercial industries is the interplay, or even competition, between what are generically designated as existing and new materials. The latter often encompasses combinations of one or more metals, polymers, and ceramics. A conclusion of this study is that there are more similarities than differences between the four primary forces driving materials research within the commercial automotive and aircraft industries: manufacturing rates, global competition, societal and regulatory constraints, and execution cycles. Advances in materials can be applied either to improve product performance, quality, and reliability or to permit creative product design to provide new, uncontested competitive space in the marketplace. The common materials needs, and thus the long-term focus, for both industries are for cost-effective, easily manufacturable, lightweight, structurally efficient, strong, environmentally benign, recyclable materials. This report has explored how these somewhat parallel needs could manifest themselves in the identification of a long-range research agenda for the industries over the next two decades.

AUTOMOTIVE INDUSTRY

The committee believes that improved materials and materials processing will play an increasingly important role in improving the competitiveness of the U.S. automotive industry. Further, the possibility of added costs will not necessarily inhibit their introduction. Provided that the performance improvements enabled by the new material are sufficiently significant, the supply of the material is stable, the processing of the material can meet the high manufacturing rates, and a reasonable prospect of widespread use exists, there is likely to be a sufficient reduction in the cost of the advanced material to spur its application.

Some of these materials-selection, and hence development, decisions will be dependent on government regulations. For example, as stated in a recent Office of Transportation Materials report, "projections of weight reductions necessary to enable automakers to meet upcoming anticipated legislative standards currently range from 30 percent to 35 percent (~1,000 lb.), with a 2,000-lb. vehicle projected as typical" (OTM, 1993). The exact level of weight reduction required will depend on advances in other technologies, such as powertrain efficiency improvements. In principle, weight reductions of this magnitude could be achieved by materials substitution, redesign of all major subsystems (body, powertrain, and chassis), and secondary weight savings. However, the impact of these substitutions on fabrication and assembly processes, vehicle reliability, and recyclability in practice is quite another matter. In order of increasing cost penalty and weight savings and decreasing recyclability, future candidates for body materials include high-strength steels, aluminum alloys, glass-fiber reinforced polymers, and graphite-fiber reinforced polymers. The final decision on usage will likely be based on how well new materials can be individually or collectively incorporated into new, advanced body-construction techniques. One intriguing possibility is the further development of unimolded body construction using polymer composites. The technological barriers here relate primarily to the higher cost of processing and the lack of available methods for recycling.

For powertrain components, decreased weight is a primary factor, along with other issues (e.g., increased power density, fuel economy, smoothness, and reduced emissions and noise). These needs will likely lead to the extensive use of cast aluminum and the gradual introduction of magnesium, titanium alloys, metal-matrix composites, ceramics, and intermetallics.

There are material-substitution opportunities for other parts of the automobile as well: the suspension and chassis and the brakes. Here again, as with the body and the engine, the issues and the drivers are the same: reduce weight by employing different materials that are cost-effective and environmentally acceptable. The committee believes these opportunities will be largely achieved in the future through the development of new, innovative processing and manufacturing approaches, using either existing materials or those currently being developed.

AIRCRAFT INDUSTRY

For the aircraft industry, while the same dominant materials drivers exist for lightweight, strong, environmentally benign materials, the considerations and the likely response will be quite different. A high sensitivity to cost of materials prevails, tempered by the need to meet high-performance requirements. Also, the materials needs of this industry are characterized by relatively small volumes at high-unit costs when compared with the automotive industry. However, similar barriers to the introduction of new materials exist, whether these are incrementally improved existing materials or those designated as revolutionary materials. Here again, the main opportunities lie in processing and manufacturing, which are estimated to account for more than 60 percent of the cost of a successful aircraft program. The effect of material type, processing, and manufacturing routes on environmental impact, recyclability, safety, and energy use need to receive increased attention, as does potential "noise pollution."

The opportunity exists for future airframe and engine materials to change from monolithic, metal-base alloys to ceramics, both monolithic and composites, and graphite-epoxy type composites. These changes will be driven by cost, weight, processing, and operating environment considerations. Candidate materials for high-temperature environments include the carbon fiber-reinforced thermoplastics and thermosets, such as the cyanate esters and toughened bismaleimides, for airframe materials and TiAl and ceramic-matrix composites for engine materials. Anisotropic materials will also become increasingly important, as will surface and interface engineering to optimize desired engineered structures by creating uniformly graded materials.

GENERAL RECOMMENDATIONS

The general materials research recommendations that impact both the automotive and aircraft industries are as follows:

- A systems approach to materials science and engineering should be adopted for enhancing existing materials and developing new materials in a cost-effective, competitive manner. *This systems approach should include consideration of the material life cycle of the product and successful paradigms for processing of materials, manufacturing of components, and measuring inservice performance*.
- Computer-based modeling is needed to integrate and assess the costs and benefits of the continued use of existing materials versus the introduction of new materials. The critical issues are processing, properties, joining, repair, and recycling.

- For automotive and some aircraft applications, research should focus on the development of a master aluminum alloy for wrought applications, the properties of which could be adjusted through processing rather than by alloying. This would eliminate the need for materials separation before recycling and would greatly foster wrought-to-wrought recycling.
- Cost-effective, lightweight, strong, environmentally benign, easily manufactured, and recyclable materials are required for both industries. These goals can best be met with the materials specified in Tables 3-2 and 3-3 in Chapter 3, such as aluminum, magnesium, polymer composites, metal-matrix composites, intermetallics, and ceramics. For instance, the development of low-cost, reliable processes for manufacturing and recycling composites will be key to their increased use.

It is clear that the more detailed analyses and conclusions are consonant with the broader vision of the Federal Coordinating Council on Science, Engineering, and Technology report quoted in Chapter 1 and further that the results described for materials for the transportation industries in this report have broader applicability to other industrial sectors dependent on advanced structural materials.

1

Introduction

BACKGROUND

The goal of this study was to determine a materials research agenda for the automotive and commercial aircraft industries during the next two decades. The National Science Foundation (NSF) selected these two industries to be the focus of this report because they exemplify in the broadest sense the challenges, successes, and disappointments of a worldwide economy, where competitiveness through innovation and productivity determines "winners and losers." The contrasts and similarities of these industries are presented in Table 1-1. Collectively, they have an important role in the U.S. (and the world) economy. In the United States, their combined sales of $156 billion in 1991 composed roughly 3 percent of the gross national product, and over one million workers were employed in direct and allied industries.

The importance of these two industries to the country can be clearly seen in the report on the much heralded federal program in materials science and technology, entitled *Advanced Materials and Processing Program*, recently issued by the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) of the Office of Science and Technology Policy. The program recommends a supplement to the President's fiscal year 1993 budget to provide a total of $1.8 billion for materials research and development, which is

TABLE 1-1: Comparison of Salient Facts Between U.S. Commercial Aircraft and Automotive Industries for 1991.

FACT	CIVIL AIRCRAFT[a]	AUTOMOTIVE[d]
Gross Sales	$38 billion[b]	$118 billion
Balance of Trade	$22 billion surplus[b]	$36 billion deficit
No. of Employees	334,000[b]	743,210[e]
Units Produced	589[c]	5.4 million
Value Per Unit	$46 million[c]	$16,152
Estimated Value Per Pound	$300[c]	$5

[a] Source: AIA, 1992

[b] All civil aviation

[c] Transport aircraft only (excluding helicopters and light aircraft)

[d] Passenger-car fleet only (Source: MVMA, 1992)

[e] Motor vehicle and parts manufacturing only

a 10 percent increase over the fiscal year 1992 budget. The materials issues for the commercial-transportation sector are stressed in a number of places in the report, for example:

> Specifically, materials advances would reduce the weight and increase the operating efficiency of future commercial aircraft. For example, advanced metals and composites, innovative structural concepts, and improved fabrication processes would offer opportunities to make stronger and more cost-effective primary wing and fuselage structures (FCCSET, 1992, 29).
>
> . . . for a new generation of supersonic commercial aircraft. . .advanced ceramic and intermetallic composites would enable the development of affordable engines operating with reduced emissions and at acceptable noise levels, and advanced aluminum alloys and composites would help reduce airframe weight (FCCSET, 1992, 29).
>
> Other advances would help the development of more fuel-efficient cars. . .opportunities lie in the development of processing and fabrication technologies for lightweight composites, high-strength metals, and tough ceramics, that will enable mass production and recycling at acceptable costs. . . (FCCSET, 1992, 30).

NSF also hopes that the materials issues for the commercial aircraft and automotive industries could have applications to other industrial and transportation sectors dependent upon advanced structural materials, such as the construction, rail, and marine vessel industries.

CASE STUDIES FOR THE REPORT

Since many of the materials issues are best illustrated by considering specific examples, and to focus the study further, a case study from each of the industries was selected for discussion within the report. The committee selected two from a number of exemplary systems that were proposed by the respective committee experts at their first meeting: the high-speed civil transport (HSCT) for the aircraft industry and the energy-efficient vehicle for the automobile industry (i.e., the 50-mpg, 5-passenger sedan). These two examples were chosen because both are seen to be potential commercial industry priorities during the next 10–20 years and could benefit from extensive materials innovations.

The HSCT, which is expected by the National Aeronautics and Space Administration (NASA) and Boeing to be introduced into service in approximately 15 years, responds to a growing market for long-range, international commercial aircraft. System studies have suggested that a high-speed transport with the properties shown in Table 1-2 may be economically viable. Key technologies have advanced since the introduction of the Concorde over 20 years ago, and further research is currently being funded by NASA. Market studies have suggested that by the year 2015, 32 percent of international travelers, some 600,000 passengers per day, might utilize a service that could be provided by an HSCT (Boeing Commercial Airplanes, 1989; Douglas Aircraft Company, 1990; Peterson and Holmes, 1991). As stated above in one of the quotes from the FCCSET report, materials advances are integral to the development of this new generation of supersonic commercial aircraft.

The HSCT was selected as the aircraft case study for two reasons. First, the severe service environment of the HSCT provides a "worst case" target for materials development. The materials requirements for the HSCT are far more rigorous than for subsonic aircraft. Materials and structures innovations developed for the HSCT would be applicable to subsonic aircraft, whereas the converse would not necessarily be true. Second, the more extreme operational requirements of the HSCT aircraft also means that a broader spectrum of technologies (e.g., polymeric composites, advanced metallics, ceramic and metallic matrix composites, sealants, adhesives, and finishes) must be investigated than for subsonic aircraft. Thus, as a case study for materials, the HSCT provides a wide range for discussion.

TABLE 1-2: HSCT Market Requirements (Source: Boeing Commercial Airplane Group).

Market Coverage:

250 to 300 passengers
5,000 nmi initial range with growth to 6,500 nmi
Efficient operation on Atlantic/Pacific routes

High Use:

Conventional airport operation
1-hr turn time
Highest economical Mach number

Passenger Acceptance:

Significant time savings
Comfort equivalent to subsonic
Accelerations similar to existing subsonic
Seat cost no more than 10–15% above subsonic

Environmental Acceptability:

Not significantly impact stratospheric ozone
Quiet airport operation similar to Stage III subsonic
Not produce perceptible boom over populated areas

The 5-passenger sedan is a mainstay of the U.S. automotive industry. Even 15 years after the energy crisis of the 1970s, midsize and large sedans still account for almost 40 percent of the U.S. sales market, the same combined market share as in 1975 (EEB, 1992). However, Corporate Average Fuel Economy (CAFE) standards are expected to increase in the future. The current, most successful method for improving fuel efficiency is to reduce the weight of automobiles (OTM, 1993). If 5-passenger automobiles are to continue to meet CAFE standards, methods must be developed for increasing fuel efficiency without sacrificing passenger space.

2

Automotive and Aircraft Industries

The development of a materials research agenda for an industry requires an initial analysis of the environment in which the industry operates and the goals that it is attempting to achieve. This chapter discusses four primary environmental forces that are currently impacting the materials-selection process and driving materials research within the two industries: manufacturing rates, global competition, regulatory constraints, and execution cycles.

MANUFACTURING RATES

The first industry pressure that is driving materials research for the two industries is manufacturing rate. The rates discussed in this section pertain to the number of units produced during a one-year period.

Automotive Industry

The automotive industry is a producer of products that must be affordable to a huge and diversified market (Table 1-1). As such, the rate of manufacturing must be extremely high. For instance, some automobile plants produce 400–500 steel panels per hour and 1500 vehicles per day. The entire U.S. automotive industry consumes about

24 million tons of materials annually, including steel, cast iron, aluminum, and plastics (MVMA, 1992). The finished value of the vehicle per pound is only about $5, however, and the dominant material, steel, costs only 35 cents a pound. In 1989, the automotive industry accounted for about 14 percent of the U.S. consumption of steel, 16 percent of aluminum, 10 percent of copper, 23 percent of zinc, 68 percent of lead, 60 percent of malleable iron, and 48 percent of rubber (MVMA, 1992).

These data reveal two important factors that are driving materials research within the automotive industry. First, the tremendous materials demand necessitates that the raw materials be generally available. The automotive industry will not adopt any material that cannot be reliably produced in the large quantities required within the specifications demanded. *Materials research must be aimed at developing inexpensive new materials that can be dependably and faithfully produced in large quantities*. Second, the processes developed for forming the materials into the required shapes must be capable of producing highly reliable parts and assemblies at true mass production volumes and uniformly consistent quality, yet the amortized tooling cost must be low to keep the cost of the finished automobile within consumer standards. *Fabrication-methods research must ensure that any new techniques are mature, dependable, and inherently capable of satisfying demand*.

Aircraft Industry

The number of units produced per year by the U.S. civilian aircraft industry is three orders of magnitude less than that for the automotive industry (Table 1-1). The aerospace industry shipped a total of 2,500 civil and 1,150 military aircraft in 1991 (AIA, 1992). On average, the finished value per pound is $300 for commercial transport aircraft. The use of relatively advanced materials combined with the production of intricate component forms without net-shape processes contribute to this higher cost per pound. The airframes of commercial aircraft are currently largely aluminum (70–80 percent) with smaller weight fractions of steel, titanium, and advanced composites. The gas turbine engines that power these aircraft use alloys of nickel (~ 40 percent), titanium (~ 30 percent), and steel (~ 20 percent), with the balance being advanced composites and aluminum.

Although the production rates for the commercial aircraft industry may be lower than the automotive industry, labor productivity, manufacturing methods, and customer requirements have similar implications concerning materials research. First, the materials used by the aircraft industry are generally more advanced and comparatively rarer than for other industries. *Suppliers for aircraft materials must show that the manufacturing processes developed for new materials can produce sufficient quantities to satisfy demand*. Second, the complexity of the aircraft and the potentially catastrophic consequences of errors demand that part fabrication be reliable. *All new fabrication processes developed must be shown to be fully reproducible and able to maintain tight tolerances and high safety standards*. Third, materials developments are closely tied to the requirements of the customer. Although there is steady pressure to employ higher-performance materials to gain market advantage, such pressure is tempered by a high sensitivity to cost. *Issues of cost and cost-effectiveness are very important to the aircraft industry. Any new material must be similar to the previous material in procurement costs, fabrication flexibilities, and scrap disposition and recycling capabilities*.

GLOBAL COMPETITION

The second force affecting materials research for both industries is global competition. Both industries operate in highly competitive global marketplaces that rely, to some extent, on material developments to maintain market share.

Automotive Industry

The automotive industry currently has extensive foreign and domestic competition. The automobile sector of the U.S. economy had a trade deficit of $36 billion in 1991. Japanese imports reached 30.7 percent of the U.S. automobile sales for the first half of 1992, and the number of Japanese transplant facilities for vehicle assembly and parts manufacture accounted for 22 percent of the cars built in North America (MVMA, 1992). This intense competition is driving the global market to attain higher levels of quality, reliability, innovation, and niche market segmentation while reducing cost and product lead-time. For instance, Japanese companies have shortened their product lead-time from 5 years to 3 years. This allowed Japanese manufacturers to replace 97 percent of their models during the 1986–'91 period, while U.S. industry only replaced 59 percent (Womack et al., 1990).

New materials technology can have a significant impact on global competitiveness. This new technology can be applied either to improve automotive performance, quality, and reliability or to permit creative product design to provide new, uncontested competitive space in the marketplace. For instance, materials processing innovations are becoming more important with the trend toward increased market segmentation as each company seeks out niche markets. More "customized" models will become available for a given segment, and the economical volume per segment will decrease from a typical level of 250,000 units to the range of 100,000 units and lower for some segments. *New materials with more flexible processing methods are needed to permit simple, rapid retooling of automotive manufacturing lines to reduce product lead-times and to allow smaller, niche-production runs, while also offering clear advantages over previous technologies.*

Aircraft Industry

The U.S. commercial aircraft industry currently enjoys the dominance of its markets, both domestically and internationally. In 1991, a year when the United States as a whole experienced a merchandise trade deficit amounting to $73.6 billion, the U.S. civil aviation industry had a positive trade balance of $22 billion (Table 1-1).

Significant shifts in its market share have occurred, however. In 1970, the United States share of the world market (excluding the group of nations led by the former Soviet Union under the Council for Mutual Economic Assistance) was almost 80 percent; in 1990 its share was less than 60 percent of the market. To date, the European aircraft industries have provided the most formidable competition to the United States.

The Asia-Pacific Rim aircraft sector consists of 23 countries including Japan, Australia, South Korea, Singapore, and China, which were the five largest importers of U.S. aircraft products within this sector during the 1986–'90 period. The trade surplus with these countries has been significant. Countries in this region are seeking bigger shares of this global industry, and their aircraft industries are growing rapidly. Undoubtedly, Japan will become a competitive force in segments of the industry such as aircraft parts and propulsion systems.

Recent events in eastern Europe and the former Soviet Union provide opportunities and potential challenges to the U.S. aircraft industry. The opening of these countries to the West creates a large future market. However, at the same time, their conversion to a commercial, export-oriented industry may result in serious competition where their technology is equal to or nearly equal to that of the United States.

The United States now has serious competition in the development of advanced-technology commercial airframes. As a result, the U.S. aircraft industry could lose its dominance in the future as foreign manufacturers continue to develop. For example, the U.S. commercial aircraft industry is meeting stiff competition in the application of advanced technologies to reduce weight and improve performance. Six foreign composite airframes and 10 major sets of secondary airframe components have been, or will shortly be, certified by the Federal Aviation Administration compared with three domestic composite airframes and 13 sets of secondary airframe components (NMAB, 1991). *One way that U.S. aircraft industries can maintain their edge within the global market is to lead in the cost-effective application of advanced materials.*

SOCIETAL AND REGULATORY FORCES

Societal and regulatory forces have a major impact on materials research for both industries, although their effect on the automotive segment has been more obvious because of the larger numbers of cars on the road.

Automotive Industry

A large force shaping the automotive industry is the trend toward fuel economy, low vehicle emissions, safety, recyclability, and low manufacturing emissions and waste. In the early 1970s, the federal government began reacting to consumer concerns by passing a sweeping set of federal regulations.

Energy

America's era of "energy complacency" ended in late 1973 when OPEC (Organization of Petroleum Exporting Countries) quadrupled the price of oil overnight. Rising energy prices and growing dependence on foreign oil ushered in fuel economy regulations. General concern has intensified since the country's dependency on imported oil rose from 36 percent in 1981 to 45 percent in 1990 (EIA, 1990, 1991a). Moreover, over 60 percent of the total U.S. consumption of petroleum is related to passenger cars and light trucks (EIA, 1991b). As a result, there is increasing pressure in Congress to mandate greater fuel economy standards for highway vehicles. Since 1975, the fuel economy for the average new car has risen from 15.8 mpg to 27.8 mpg, a 76-percent increase (EEB, 1992).

Several bills have been introduced in Congress that would require the fleet average to increase well beyond the current standard. It is possible that CAFE standards may be set as high as 40 mpg. Since a 10-percent weight reduction in an automobile can increase fuel economy by five percent (EEB, 1992), the automotive industry has increased its reliance on advanced, lightweight materials (e.g., high-strength steel, cast and wrought aluminum, and nonstructural plastics; Figure 2-1). However, the higher cost of lightweight materials and the more expensive and less flexible processes for manufacturing parts has currently restricted their use. *Future increases in fuel economy will demand further improvements in lightweight materials and their processing techniques to reduce vehicle weight even further without substantially increasing cost.*

Environment

Global environmental and natural resource issues will greatly impact product technology of the future, especially increased concern with CO_2 emissions. Since the mid-1970s, catalytic converters have been installed in all new cars to reduce tailpipe emissions (Figure 2-2). New federal legislation passed in 1991 will require greater reductions in tailpipe emissions (EEB, 1992). For 1994, the mandated emissions standards for passenger cars of 6,000 pounds gross vehicle weight or less will be non-methane hydrocarbons at 0.25 grams/mile, CO at 3.4 grams/mile, and NO_x at 0.4 grams/mile. The government may invoke stricter standards by 2004 (i.e, non-methane hydrocarbons at 0.125 grams/mile, CO at 1.7 grams/mile, and NO_x at 0.2 grams/mile).

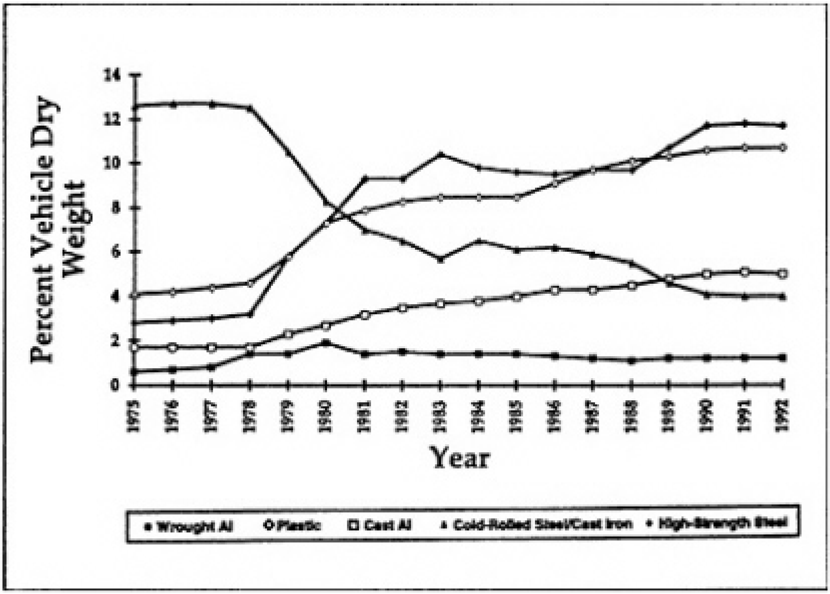

FIGURE 2-1:
Trend in increase of lightweight materials to improve fuel economy of automobiles (Source: Ford Motor Company Research Laboratory).

States are also setting their own standards. California is invoking strict standards at a faster rate, requiring that the 1994 federal levels be implemented in 40 percent of the California fleet by 1993. California will also require 2 percent of their fleet to be *zero* emission vehicles by 1998 and 10 percent to reach this goal by 2003.

These regulatory forces have already had a major impact on automotive product technology and materials usage in several major areas, such as the addition of emission control systems that include materials new to the industry (e.g., noble metal catalysts that simultaneously control HC, CO, and NO_x; ceramic honeycomb catalyst supports; and 409 stainless steel converter cans) and the addition of electronic control systems. The initial use of electronic control systems to control the air/fuel ratio for three-way catalysts has resulted in the introduction of: engine control computer systems using sophisticated microprocessors (the automobile industry is now the largest volume purchaser of silicon chip devices); exhaust gas oxygen sensors, containing oxygen ion-conductive ceramic electrolytes; and capacitive pressure sensors, fabricated by micromachining silicon. *New catalytic materials, new materials for reliably sensing tailpipe gases, and advanced electronic control systems can reduce tailpipe emissions even further.*

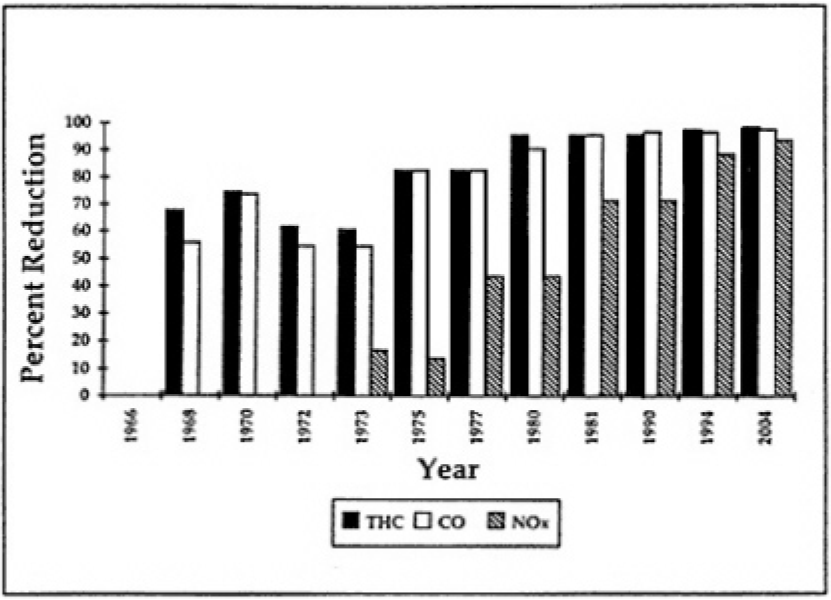

FIGURE 2-2: Reduction in state passenger-car tailpipe emissions since 1966 (Source: Ford Motor Company Research Laboratory).

Disposal

Disposal of solid wastes and toxic materials is a growing concern. Landfills are filling up, new sites are difficult to find, and disposal costs are rising rapidly. This will bring increased pressures for recycling regulations in the United States. Germany has proposed laws that will force the automobile industry to buy cars back from the final owner; Ford and BMW have already instituted pilot buy-back programs.

There are two main problems hindering recycling and disposal programs. First, automobiles have to be disassembled and the materials separated before recycling in order to prevent contamination and to remove those materials that cannot be recycled. BMW has extensively studied the disassembly of discarded vehicles, and many companies are embracing the newly formed discipline of environmentally conscious design of products and processes. *New methods for separating materials are required to ensure the proper disassembly and recycling of materials* . Second, many advanced materials simply cannot currently be recycled. *Methods are needed to permit the recycling of many of the advanced materials that at present can only be disposed of in land fills.*

Aircraft Industry

Energy

In response to the rapid increase in fuel prices experienced in the early 1970s, engine and airframe manufacturers gave increased attention to the energy efficiency of aircraft. Some scenarios projected that the cost of fuel would continue to increase and become a major part (some 40 percent) of aircraft direct operating costs (DOC) during the 1980s. Instead, the price of fuel returned to a relatively stable and low level. Fuel costs still represented in 1990 only roughly 18 percent of DOC (ASEB, 1992), which is still less than half of the earlier estimate. New engines were developed to maximize fuel efficiency and engine durability. However, low initial cost (i.e., not much different than that of mature engines) proved to be a more important attribute in terms of market acceptance.

Over the past 25 to 30 years, the fuel efficiency of large commercial aircraft has almost doubled from 40 seat-statute miles per gallon of fuel to approximately 80 for the most recent aircraft (e.g., Boeing 767). Although the importance of fuel costs in the DOC equation has not realized the mid-1970s projection, it cannot be ignored, and the trend toward more efficient airframes (and engines that power them) will continue. *Airframe manufacturers require new advanced materials to reduce airframe weight and permit reductions in propulsion energy by 10 to 30 percent*. Engines can also be made more efficient by both new designs (e.g., the propfan) and component improvements (e.g., gearboxes, compressors, combustion chambers, and turbines). *New materials systems and devices are required to reduce airframe and engine weight and further increase fuel efficiency* (Barrett, 1992). As stated in the NASA-sponsored Boeing report on the HSCT: "The data show that, collectively, advanced technology reduces the MTOW [Maximum Takeoff Weight] from 1 million pounds to 745,000 pounds (about 25%) with advanced structures and materials providing the largest single benefit" (Boeing Commercial Airplanes, 1989).

Environment

Aircraft are minor contributors to pollution (less than 3 percent of the carbon dioxide produced by fossil fuel use), and the environmental impact of aviation has generally attracted little attention. Nonetheless, since air travel (both international and domestic passenger and freight transport) is one of the fastest growing energy-use sectors, the environmental concern of the effects of combustion products—especially CO and NO_x—on the atmosphere at high altitudes (~ 10 km), will become increasingly significant. NO_x is already viewed as a principal factor in determining the operational feasibility of the HSCT and a driver of combustion technology. One way to reduce engine emissions is to improve fuel efficiency. *Environmental concerns about aircraft emissions will also drive the same improvements in the operational efficiencies of engines and airframes, as discussed in the aircraft Energy section above*.

Although the quantity of materials used by the civilian aircraft industry is far less than that used by the automotive industry, specific manufacturing issues relating to environmental impact, safety, and energy that were often treated as being of secondary importance in the past are receiving increased attention. State and federal regulations related to the handling and disposal of toxic materials used during manufacturing (e.g., disposition of spent chemical baths and recycling and scrap disposal) have become far stricter during the past few years. *Increased concern for safety and energy savings will drive research for environmentally benign manufacturing processes*.

Commercial aircraft noise is also subject to strict regulations. For example, the United States has established rules that will require complete phase-out of operations by the early 21st century of jet-powered airplanes that do not meet Stage 3 noise-level standards (Federal A viation Regulation 36). These regulations or noise standards set by local airports place design constraints on new powerplants and require in-service airplanes powered by older design, lower by-pass ratio engines to be retired, re-engined, or retrofitted for noise abatement (e.g., "hushkits" for JT8D-powered airplanes). Noise control compromises engine performance, however, such as by the addition of parasitic weight through the unavoidable use of heavy, acoustically absorbent materials (Marsh, 1991). *Research is required for better acoustically absorbent materials and for materials systems and designs for quieter engines.*

PLANNING AND EXECUTION CYCLES

The planning and execution cycles within the two industries also affect the materials selected and the time required to adopt new materials.

Automotive Industry

On average, planning for a new vehicle by a U.S. manufacturer begins 62 months before production, advanced engineering begins 56 months before production, and process engineering begins 31 months before production (Clark and Fujimoto, 1989). Thus, new materials and new material processing technologies must be fully developed roughly five years before actual production use. Although competitive pressures are forcing these times to be reduced (overall lead-times are moving from 5 toward 3.5 years), the intense emphasis today on reliability and quality means that the task of developing new automotive materials and processes well in advance of production is more critical than ever. *Before any new material or process is approved for production, the company must have high confidence in its reliability, cost, performance, and environmental impact throughout its full cycle of processing, use, service, and disposal*.

The time required to design and process existing materials is a major component of lead-time. Particularly important is the time required for designing and machining major dies for exterior body panels. In the growing trend to reduce time to market, new materials are typically avoided because of the time and cost required to test them. There is growing confidence in the accuracy of computer assessments of design integrity, but costly and time-consuming testing is still required to verify designs of automotive components and systems. *A materials development approach that incorporates increased use of computer simulation can reduce lead-times and costs in the automotive industry*. An example of where this has worked is in sheet metal stamping where fundamental considerations of constitutive behavior have been used to speed the design of dies for complex parts through the use of computer simulation (Wang and Tang, 1985).

Aircraft Industry

The acceptance of new materials in the commercial airframe and engine industries is delayed by long planning and execution cycles. The materials for new aircraft and propulsion systems planned for initial operation in 2005 will be frozen during the next two or three years. Preliminary planning for 2015 product systems is underway and broad macroeconomic planning for 2025 can rationally be undertaken. *New materials and new material processing technologies for the civil aircraft industry require roughly 2 or 3 times longer to implement than for the automotive industry*.

Nonetheless, aircraft systems designs push the capabilities of structural materials as no other industry does. The principal factors for structural applications of aircraft materials involve considerations of life-cycle costs, strength-to-weight ratios, fatigue life, fracture toughness, corrosion resistance, and reliability. Even when a newer, more advanced material can apparently be used to some advantage, the issue of safety and service-life warranties bias designs and materials choices toward preexisting materials. This is especially true in civil aircraft. As a result, the use of newer materials is severely inhibited in the commercial sector as far as primary structures are concerned. Because advances are so dependent on significant improvements in materials capabilities, complex design and cost trade-offs are performed. Competing solutions to the same envisioned problem must be explored and evaluated in parallel, with a corresponding multiple-cost impact. Production volume may be so low and lead-time from design to production so long that the selected materials may be a generation or two behind the state of the art before they find real application. *Basic materials work should be initiated in anticipation of future system needs even though specific needs may be ill-defined. This work should be done a partnership involving user and supplier industries*.

SUMMARY

Although there are some stark differences between the commercial automotive and aircraft industries, the information presented in this chapter reveals many similarities in their current and projected materials needs (Table 2-1). However, the materials solutions will have to be different for the two industries. The civil aircraft industry will require that the materials applications be increasingly met with high-performance new materials, while the automotive industry will continue to require the lowest-cost materials to keep the product universally available. Chapters 3 and 4 detail the future materials research priorities for both of these industries.

Table 2-1 Comparison of the Four Primary Forces Driving Materials Research within the Civil Aircraft and Automotive Industries.

	Automotive Industry	Civil Aircraft Industry
Manufacturing Rates	Readily available supply of materials required. Materials capable of high processing rates. Materials capable of low amortized tooling costs. High reliability/quality of finished parts/assemblies. Fabricated component cost must be low (i.e., <$5 per pound).	Stable supplier base for advanced materials required. High reliability/quality of finished parts/assemblies. Materials tied to customer requirements/cost issues. Materials cost must meet $300/lb for civil transport aircraft.
Global Competition	Increasingly internationally competitive field. Product must be affordable to large/diverse market. Impact of changing commercial market causing shift to "niche" production. New concepts/designs will demand new materials. New materials required to improve performance/ quality/reliability. New materials must offer clear advantages.	Increasingly internationally competitive field. Product must meet customer requirements/cost issues. Impact of growing commercial travel market causing demand for new aircraft (i.e., HSCT). New concepts/designs will demand new materials. Improvement of performance/safety/reliability will require new, less forgiving material combinations. New materials must offer clear advantages.
Societal and Regulatory Constraints	More stringent regulations will drive new materials for emissions/fuel economy at low cost. Reduced weight for fuel economy. Normal operations must meet safety/environmental regulations. Finished products must be environmentally stable. Methods for recycling many materials required.	Environmental/recycling concerns will drive reliance on leading "materials R&D power curve". More efficient airframes/engines for fuel economy. Normal operations must meet safety/environmental regulations. New aircraft needs structurally/environmentally stable, high-temperature materials.
Execution Cycles	New materials must be developed 5-years prior to production. New materials must show improvements in life cycle reliability/cost/performance/environmental effects. New materials must fit into existing processes to meet production cycle and minimize added cost.	New materials must be developed 10–15 years prior to production. New process/manufacturing paradigms require early introduction of material constraints into design. Greater reliance on rapid introduction of intelligent processing of materials.

3

Materials Research Agenda for the Automotive Industry

General and specific materials research opportunities were determined for the automotive industry using the 50-mpg, 5-passenger sedan as a basis for analysis. The general finding highlights the need for developing a materials-systems methodology and for approaching research issues in terms of the materials life cycle. The specific findings address advanced materials candidates and corresponding research needs for the major component subsystems of the vehicle.

NEED FOR MATERIALS-SYSTEMS APPROACH

Improved materials and materials processing can and must play a large role in generating productive and effective responses to the forces that will drive the automotive industry in the future. However, these forces often pull in diverse directions when specific technological actions are considered. For example, aluminum alloys can be used to reduce vehicle weight, thereby reducing emissions and improving fuel economy, but the added materials costs currently offset these advantages for many applications. As a result, steel is still the major material of choice for automobile construction today and will be difficult to supplant for the foreseeable future.

Added costs are not the only inhibitor to the use of advanced materials. For example, if a breakthrough in processing dramatically reduced the cost of graphite fibers, there would not necessarily be an immediate large-scale application of graphite-reinforced polymer composites to automobile construction until a suitable supplier infrastructure was developed, a reliable process was available for fabricating polymer-composite parts in high volume, and a well-defined mechanism for recycling these materials was found. Thus, in conducting R&D on new materials and processes for automotive applications, a comprehensive "systems" view must be adopted so that, in this larger context, the demanding and often conflicting requirements of the full automobile system can be taken into account.

Materials Life Cycle

Another aspect of the materials-system approach is the consideration of the materials life cycle as shown in Figure 3-1. There is a growing realization that all phases of the cycle should be considered in product and process design. This new paradigm for design can be called environmentally conscious design or "green" engineering, by which is meant:

> . . . an approach to product/process evaluation and design for environmental compatibility that does not compromise product quality or function. In this framework a "green" product is both environmentally compatible and commercially profitable (Navinchandra, 1991).

A life-cycle view of a product includes the following costs: manufacturing, transportation, packaging and its disposal, treatment of hazardous by-products, operational use, maintenance, and disposal. If the product or its use is environmentally incompatible (e.g., involves the use of hazardous materials), then these costs must also be considered during product, materials, and process selection.

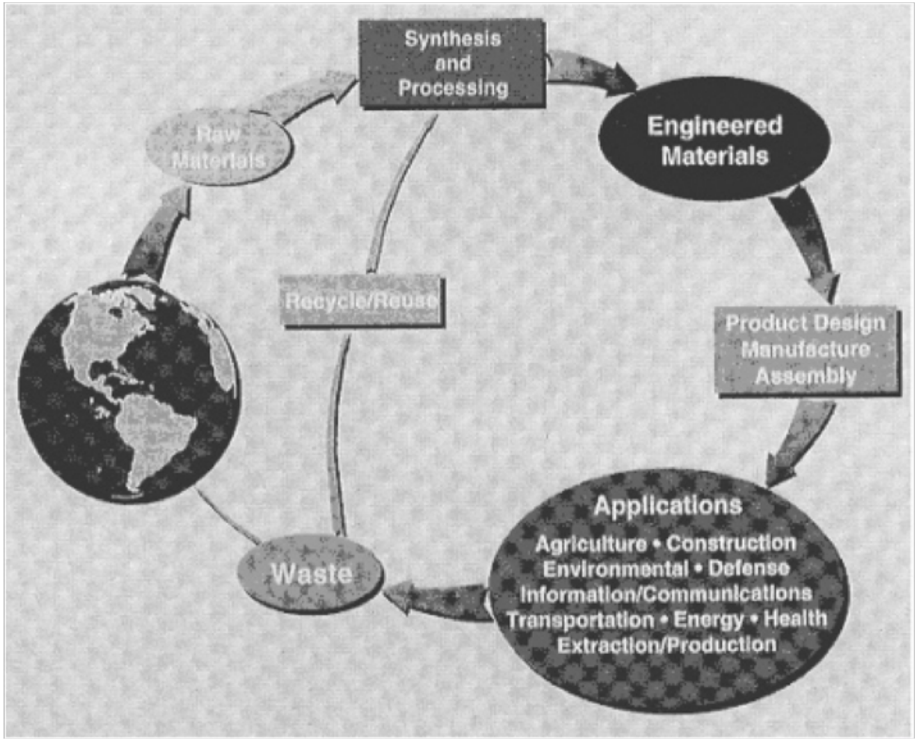

FIGURE 3-1:
The total materials cycle (FCCSET, 1992)

From a systems consideration, controls include market and industry requirements, federal legislation that mandates safety, fuel economy, and emissions standards for the product, and waste management requirements. Although the majority of standards on waste management today are imposed at the factory, recycling of the product when customers no longer have use for it will be a major concern in the future, particularly for the automotive industry because of the large number of vehicles that are disposed of each year.

Modeling of Materials Systems

This new total-materials-cycle paradigm for design will rely heavily on computer modeling of all aspects of materials systems. Computer-modeling techniques are needed to assist in developing and evaluating the product's performance and reliability, the materials-selection process, the synthesis and processing of materials, and the fabrication of materials into components. Micro-models of materials behavior and phenomena (e.g., mechanical and thermodynamic) are also required, particularly to facilitate the design of engineered materials.

Materials-Systems Research

Unfortunately, much of the materials research at industrial and university laboratories has been driven by the search for improved materials properties with minimal attention paid to this systems approach. If researchers at academic institutions are to have significant impact on materials usage in the commercial automotive and aircraft industries, a new paradigm for prioritizing and guiding the research efforts must be found that defines goals at both the basic and applied levels in terms of the long-term system drivers. Collaboration between university and industry investigators should be pursued, because system-driven problems demand that multiple viewpoints and skills be involved in planning and developing effective solutions.

MATERIALS RESEARCH NEEDS FOR AUTOMOTIVE COMPONENT SUBSYSTEMS

This section presents specific findings concerning the advanced-materials candidates and the corresponding research opportunities for the major component subsystems of automobiles.

Lightweight Materials for Body Structure

If market-driven requirements or government fuel-economy regulations specify 40 mpg or higher in the future, it will be necessary to reduce the average vehicle weight of the U.S. fleet by 500–1000 pounds, assuming that a 10 percent weight reduction yields a 5 percent increase in fuel economy (EEB, 1992). For family-size (5–6 passengers) vehicles to meet such regulations, this sizeable weight reduction will require the application of lightweight materials throughout the vehicle, particularly in the body structure and closure panels, as well as in other large components in the engine, transmission, drivetrain, suspension, and brake subsystems.

Body Materials

Compared with mild steel, lightweight material candidates for body components are high-strength steel, glass-fiber reinforced polymers (FRP), aluminum alloys, and graphite-fiber reinforced polymers (GrFRP). Table 3-1 shows that while high-strength steel can be cost-effective, only about 10 percent weight savings can be achieved. Aluminum alloys can and are being applied today with weight savings in the range of 40–50 percent, but the cost penalty for wrought products in these applications is substantial. FRP could be cost-effective in the long-term and can result in weight savings of 25–35 percent. At present, GrFRP materials are far more costly than the other alternatives, but they are attractive because weight savings of 50–65 percent can be realized. GrFRP is being reconsidered due to recent forecasts of lower graphite fiber prices.

TABLE 3-1: Lightweight Materials: Relative Component Costs and Weight Savings (figures based on Ford Motor Company's cast modeling program)

	Relative Material Cost (per lb.)	Approximate Relative Component Cost	Weight Savings %
Cast Applications			
Cast Iron (Base)	1.0	1.0	Base
Cast Aluminum	1.8–2.2	1.0	50–60
Cast Magnesium	3.0	1.0	65–75
Body Structural Applications			
Mild Steel (Base)	1.0	1.0	Base
High-Strength Steel	1.1	1.0	-10%
Aluminum	4.0	2.0	40–50%
FRP	3.0	0.8[c]	25–35%
GrFRP	10[a]–30[b]	1.25[a]–2.25[b,c]	50–65%

[a] 50% Graphite fiber at $6/lb.

[b] 50% Graphite fiber at $20/lb (current price).

[c] Assuming low-cost, unproven resin-transfer modeling process; with current process ratios would be 2-times higher.

Advanced Body-Construction Techniques

The use of alternative materials in the vehicle body to achieve large weight reductions will very likely be accomplished through the use of new body-construction techniques. As shown in Figure 3-2, one approach is to use a lightweight aluminum space frame that supports the major body loads, especially during crash situations. The space-frame sections can be joined by welding or adhesive bonding. The closure panels can be either aluminum or composites (i.e., FRP or GrFRP), both of which could be mixed with conventional steel panels if desired.

Another approach to an all-aluminum body would be the use of stamped aluminum parts with adhesive or welded joints for body construction and stamped aluminum closure panels. In this approach, much of the industry's investment in sheet-metal-stamping technology could be retained.

Plastic composites can be used to mold entire body structures in large integrated sections. As few as five moldings could be used to construct the body using a liquid molding process called resin-transfer molding (RTM), whereas conventional steel construction would require several hundred pieces. Liquid molding has the potential for mass production, and the cost savings from low-cost tooling and part integration help to offset the incremental cost of the resin and fiber.

Lightweight Body Materials: Application Issues

For these technologies to be adopted, many development issues need to be resolved. Cost effectiveness is a key issue (i.e., will products fabricated from these materials be affordable?). As shown in Table 3-1, the relative cost per unit weight of lightweight materials is substantially greater than mild steel. On a component basis, however, the relative cost ratios are reduced due to the weight savings afforded by the lightweight material options and, in some cases, by lower tooling and assembly costs resulting from part integration.

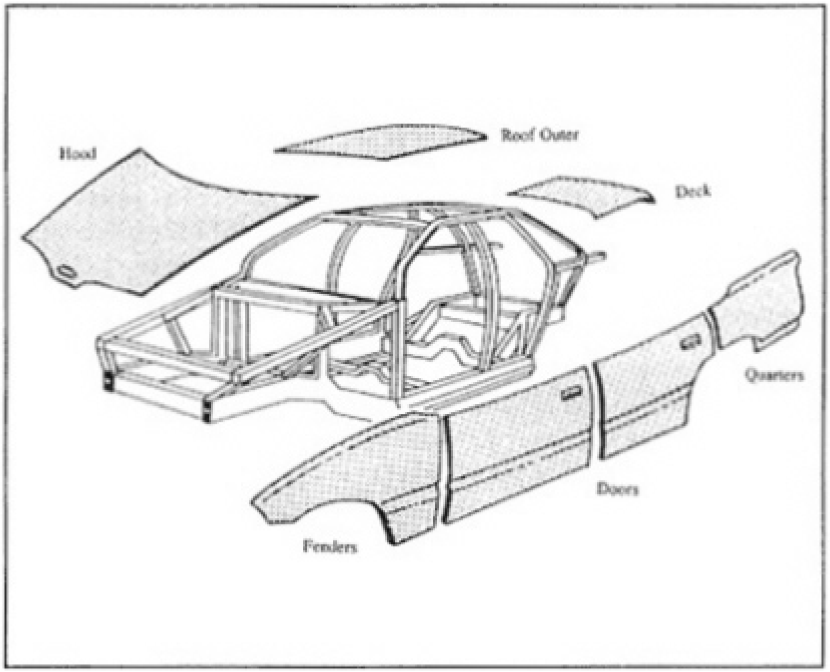

FIGURE 3-2: Lightweight aluminum space frame supporting panels of steel, aluminum, or plastic (Source: Ford Motor Company Research Laboratory).

As also indicated in Table 3-1, aluminum currently represents a substantial cost penalty over steel (two times). Crash performance and durability issues must also be resolved. Due to the high cost, Honda introduced aluminum bodies on a high-priced, low-volume, niche vehicle (i.e., the "all aluminum" NSX sports car) to gain materials insight and know-how. Over 31 percent of the weight of this vehicle is aluminum versus roughly 6 to 7 percent on today's average car. Before the NSX could be produced, many issues had to be considered:

- Forming
- Galvanic corrosion
- Heat treatment
- Ding/dent resistance
- Joining
- Alloy design
- Hot forging
- Painting

Recyclability of aluminum for sheet materials is a concern because of the high sensitivity of strength and ductility to the alloy composition. A novel research problem would be to develop a universal alloy series that differs only marginally in alloy content and that permits property changes primarily through different processing histories. Currently, the properties of aluminum can only be varied by alloying. However, aluminum scrap must then be sorted before recycling to ensure that different alloys are not combined. By developing a standard alloy that can be changed via processing and not alloying, the need for sorting would be eliminated and recycling simplified. The high volumes required of such a standard alloy may also eventually cause it to be less expensive to produce than other advanced materials. Improvements in alloy chemistry and joining technology are also needed to minimize, reliably and cost effectively, the major galvanic-corrosion concerns presented by increasingly aluminum-intensive vehicles.

Engineering plastics and polymer composites are competitors to aluminum alloys for reducing the weight of car bodies. Nonstructural plastics (e.g., polyesters and polyethylene) are utilized in interior and exterior trim, and high-performance polymer alloys, such as Xenoy^{tm}, are used in bumper applications. Reduced cost, part consolidation, styling considerations, and weight savings have all contributed to the steady growth of plastics.

For the use of structural composites, such as FRP, in major body parts, it appears that the cost penalty (i.e., higher cost of using this material) per pound saved on the automobile could be less than for aluminum (Table 3-1). With further research and development, the incremental cost per pound saved may turn out to be near zero. Manufacturing issues include demonstrating that liquid molding can be accomplished at fast cycle times and showing that highly reliable integrated parts can be produced that meet the performance specifications. Control of the molding process through feedback from sensors will be essential. Other issues associated with polymer composites that need to be resolved are crash performance, durability, repair techniques, and recyclability.

The RTM process, which has considerable promise for mass production, relies on low-viscosity thermoset resins. Whereas steel, aluminum, copper, and zinc are recovered from scrapped automobiles today and recycled into useful commercial products, recycling strategies for RTM liquid-molded composites require much more development and are a fertile area for research. Unfortunately, thermosets cannot yet be recycled effectively, but research on the pyrolysis of thermosets and their use as ground fillers in lower-grade products may ultimately lead to an effective recycling scenario. In the longer term, new thermoplastic resins that have lower viscosities and moldability properties similar to thermosets may come into use because they can be recycled by melting and remolding, or perhaps even by depolymerization. Thermoplastic RTM materials are also more crash-resistant and damage-resistant.

Secondary Weight Reduction

Primary weight reductions alone cannot achieve an average 1,000-lb. weight reduction per vehicle. It will also be necessary to take advantage of secondary weight reductions (i.e., additional weight savings in subsystems that depend on the total vehicle weight). For example, engine, suspension, and brake subsystems can be downsized for lighter automobiles, because their performance requirements decrease as the total weight of the vehicle drops. The ratio of secondary to primary weight savings can be estimated only roughly. Such analyses indicate that as much as 0.5–1.0 lb. of secondary weight reduction can be achieved for each pound of primary weight removed, provided *all or most* secondary subsystems are reduced in weight.

Material Applications For Powertrains

The demand for increased power density, improved fuel economy, stringent emission requirements, enhanced smoothness, and improved noise reduction will drive powertrain advanced-materials applications.

Engine Materials

For the next 10–20 years, the major automotive power source will be the spark-ignited, internal combustion engine.[1] Although the major fuel of choice will continue to be gasoline, the number of vehicles using alternative fuels, principally methanol and natural gas, is expected to increase. It is also likely that electrically powered vehicles will become important in states such as California that mandate zero-emission vehicles. Marked changes in engine materials should take place over the next 20 years as a result of two of the forces driving the industry: global competition and environmental considerations.

Competitiveness to increase performance and to generate more space for passengers and devices is driving greater power-to-size ratios. The importance of freeing up space can easily be understood by looking under the hood of virtually any vehicle built today. Other

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[1] The committee did not consider other engine types because of concern that they will not be acceptable in the United States within the time frame of interest to the study. Indirect and direct injected diesels are used extensively in Europe, but it is not clear that they can meet U.S. federal and California emission standards except in small cars. Diesel noise and odor problems must be solved before they will be marketable in the United States, although they have better fuel economy than spark-ignited internal combustion engines. Gas turbine engines probably will require the use of ceramic components to achieve the high inlet gas temperatures required for high efficiency and small package size. Despite many years of government funded R&D in the Advanced Gas Turbine project, the cost, benefit, and reliability relationships for the ceramic turbine are still unclear. Thus, it is unlikely that ceramic gas turbines will be introduced in passenger cars in the foreseeable future. Also, small metal-based turbines are being considered for applications in hybrid electric vehicles.

uses for this space include advanced styling concepts that lower the hood line and create opportunities for greater product differentiation and crush space for improved crash-energy management.

Power can also be increased by operating engines at higher speeds. This is an additional incentive for reducing the mass of reciprocating components and for reducing friction in the engine and valvetrain. Higher operating temperatures also favor higher power. The value added to the vehicle from new engine materials is at risk of being offset by increased variable costs and investments and by potential reductions in environmental quality. For example, although higher operating temperatures increase engine efficiency, more oxides of nitrogen are formed as combustion temperatures increase. As a result, engine temperatures are limited today by the control of NO_x emissions and will continue to be until a breakthrough occurs in catalysts or alternative fuels.

Environmental considerations, together with competitiveness, are also driving the development of engines with higher power density. Such engines can improve fuel economy by downsizing while maintaining performance at current levels. The use of lighter-weight materials (i.e., titanium alloys, metal-matrix composites, ceramics, and intermetallics such as TiAl) for the reciprocating components in the engine can improve fuel consumption and should also significantly reduce vibration and noise. Toyota has already introduced metal-matrix composites in diesel-engine pistons, and Honda has replaced cast-iron liners in aluminum blocks with metal-matrix-composite liners. Reduction in the mass of engine valves, valve springs, and valve-spring retainers can be used to reduce friction losses and improve fuel economy appreciably for a given level of engine performance. Weight reduction of the engine block itself is driving the use of thinner cast-iron walls and the introduction of more cast aluminum. A key issue for cast aluminum is to be able to eliminate the general need for cast-iron cylinder liners.

Transmission Materials

The major goal for improving transmissions is to reduce weight and size while maintaining or improving reliability, power-handling capacity, and functional characteristics such as shift quality and efficiency. Alternative materials can contribute to the achievement of this aim in several ways:

- Magnesium Transmission Housings. Replacing aluminum with magnesium will result in about a 33 percent weight reduction (10-lb. savings might be typical). The issues that must be addressed include properties at elevated temperature, cost, and development of a viable manufacturing infrastructure.
- Improved Gear Materials. Steels with better fatigue and wear resistance could allow a reduction in gear sizes that translates into an overall size and weight reduction of the transmission. Improved surface treatments can also contribute to this benefit. Among the issues are the cost of these materials and the need for extensive redesign of the transmission to realize the maximum benefits.
- Composite Materials. Both metal and polymer matrix composites have potential for application in transmission components. The potential benefits, such as weight and noise reduction, must be investigated. Other issues include cost, fabrication methods, and supplier infrastructure.

Material Applications for Chassis, Suspension, and Brake Systems

The demand for weight reduction, reliability, and durability will precipitate new material applications in chassis and suspension systems. A systems approach to developing advanced brake materials must be taken.

Suspension and Chassis Materials

A variety of material possibilities arise in considering weight reduction of suspension and chassis components. As the mechanical and ambient environments generate significant corrosion and fatigue requirements, reliability is a major concern, because most of these components are critical to safety. The candidate materials for weight reduction are listed in Table 3-1, along with some major issues that, if resolved, would lead to application on a larger scale. High-strength steel, cast steel, aluminum, and magnesium components are already appearing in some vehicle lines. Glass-fiber-reinforced leaf springs are already in production on GM's Corvette. The use of these materials will increase over the next decade.

Brake Materials

Brake systems are significant and important materials/mechanical systems that have received little attention from academic researchers, particularly from a systems viewpoint. The interaction of the brake linings and pads with the brake drum and rotor is highly complex, and even minute changes in chemistry can have large effects. The displacement of asbestos by alternative materials has proven difficult. The development of a systems science for automotive brakes, including the mechanical and materials aspects, should prove to be beneficial to both automotive manufacturers and brake component suppliers.

Metal-matrix composites offer a potential large weight savings over iron for brake drums, calipers, and rotors. The nature of the system requires that these materials be developed in concert with the friction material.

Material Applications for Exhaust and Emission Control Systems

The demand for cost reduction, improved durability, and stringent emission control requirements will drive new material applications in exhaust and emission control systems.

Exhaust System Materials

Corrosion-resistant and heat-resistant steels are currently used in the exhaust system and catalytic converter. Ferritic stainless (409) is used for the converter can and connected pipes, and austenitic stainless and super alloys are used for the wire meshes surrounding the ceramic honeycomb monolith. These components must operate continuously at temperatures in the range of 1300–1800°F, with excursions as high as 2100°F. As a result of the new ultra-low emission standards, attempts are being made to achieve faster light-off of the catalyst by insulating the exhaust manifold and replacing the ceramic honeycomb with metal honeycombs (Fe-Cr-Al alloys). Moreover, ferritic and austenitic stainless may replace alloy cast iron in some exhaust manifold applications.

To achieve greater durability, there may be increased usage of ferritic stainless in mufflers, tailpipes, and hangers, replacing Alcoated steels. These trends probably will progress slowly because of the increased cost associated with these steels. An important discovery would be low-cost, formable coated steels with substantially greater durability than currently available materials.

Emission-Control-System Materials

Platinum group metal (PGM) catalysts dispersed in ceramic monoliths, containing some rare earths (Ce), constitute the primary technology capable of meeting current emission standards in the United States and Japan and future standards in Europe and other countries. Total use of PGMs will increase due to increased use of catalytic emission controls worldwide. For cost and supply reasons, there has always been pressure to reduce the PGM content in catalysts. However, more stringent emission standards and increased regulations for in-use compliance will require increased use of PGMs in catalysts. Also, the platinum/rhodium ratio found in ore is such that excess platinum must be mined to meet the required rhodium contents in current catalytic systems. As NO_x regulations are tightened, the rhodium content will increase, exacerbating this problem. New developments have shown that lower-cost palladium can be an effective substitute for platinum in countries employing nonleaded fuels.

There have been many attempts to find a low-cost, non-noble metal catalyst that could replace the current system. These attempts have failed, primarily because base-metal catalysts and other materials such as Perovskite compounds prematurely lose their catalytic activity due to aging or poisoning. This remains a challenging area of research.

An alternative to emission control by three-way catalysts, which must operate close to the stoichiometric air/fuel ratio (14.7), is the lean-burn concept (air/fuel ratio of 20–25) that offers greater fuel economy. Whether for Otto cycle or diesel engines, this concept requires a NO_x catalyst that can operate under ultra-lean conditions. Current research in this area is directed toward zeolite-type compounds, which have open, cage-like molecular structures.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

One general finding was formulated concerning the current materials-selection methodology for automobiles and the need for a new paradigm:

> Materials for automotive applications must be viewed as part of a system. If this approach is adopted during research and

> development of new materials and processes, appropriate trade-offs can be made to reconcile the demanding and often conflicting requirements of an automobile. This new paradigm must consider the entire life cycle of a product, including the following costs: manufacturing, transportation, packaging and its disposal, treatment of hazardous by-products, operational use, maintenance, and disposal. Computer-modeling techniques must also be developed to assist in the development and evaluation of product performance and reliability, materials synthesis and processing, and materials fabrication into components to facilitate materials design and selection.

In keeping with the materials-system approach, the specific automotive-materials scientific and engineering research opportunities presented in this chapter are summarized in the form of life cycle charts in Tables 3-2 and 3-3. The matrix approach used in the life cycle charts allows the reader to cross-correlate material, application, and research required in such areas as processing, property enhancement, joining, repair, and recycling.

Table 3-2: Summary of the Scientific and Engineering Research Opportunities for Automotive Structural Materials

MATERIALS	APPLICATIONS	PROCESS	PROPERTIES	JOINING	REPAIR	RECYCLE
High-strength steel	Body, chassis, suspension, and transmission	High-volume process ■ Spray forming ■ Warm forming	Higher ductility w/o loss in strength Low variance in properties	Adhesive bonding: Precise dimensional control of stampings		
Cast iron and steel	Engine, driveline, and suspension components	Thin-wall castings Low-cost steel process	Higher strength and ductility Low variance in properties			
Aluminum alloys	Body, chassis, suspension, engine, transmission, and others	Universal alloy series High-volume spray forming Low cost Warm/Cold forming Superplastic forming	Higher elongation Improved wear resistance for engine applications Improved high-temperature strength	Adhesive bonding Spot welding	Repair science	Methods for scrap separation by alloy chemistry
Resin-base composites	Body, chassis, suspension, and transmission	Higher-speed molding Hot stamping of thermoplastic materials	Materials data base Reliable prediction of durability under cyclic loading in aqueous environment Crash-energy management of engineered structures Lower-cost fibers per unit fiber stiffness	Adhesive bonding	Repair science	Methods to recycle large volumes of materials
Self-reinforcing liquid crystals	Long-range replacement for FRP applications	Control orientation	Equivalent to FRP	Ultrasonic Adhesives	Repair science	Recycling process
Metal-matrix composites	Lightweight engine and chassis components	Low-cost fabrication techniques Near net shape	Improved high-temperature fatigue Data base	Graded junctions	Repair science	Recycling process
TiAl and FeAl	Engine components and exhaust system	Low-cost, high-volume fabrication techniques	Improved ductility	Graded junctions		Scrap separation methods needed
Titanium	Engine components and springs	Low cost	Improved machining Improved wear and fretting resistance Improved high-temperature oxidation			
Magnesium	Casings, covers, and wheels	High-volume process for cast wheels Low cost	Improved high-temperature properties Improved wear resistance			
Ceramics	Gas engine valves, roller followers; diesel engine chamber and piston	Net shape Low cost	Higher Weibull modules	Graded junctions to metal or metal-matrix composites	Not feasible	Recycling process

Table 3-3: Summary of Scientific and Engineering Research Opportunities for Automotive Nonstructural Materials

MATERIAL SYSTEM	APPLICATIONS	PROCESS	PROPERTIES	JOINING	REPAIR	RECYCLE	IMPACT
Paint and corrosion protection system	Body structures and closure panels Bumper systems	Low Emissions Non-toxic Low-volume niche applications Low-cost, precoated sheet Single-coat process	Long-term durability Good adherence and appearance after forming	Not applicable		Not recoverable in plant or from discarded vehicles	Minimize paint to lower emissions, cost, and waste
Wear and friction materials and coatings	Engine cylinder bores, valvetrains Brake and clutch systems Geartrains	Low-cost, high-volume capability for coatings	Low friction and high wear resistance for engine applications	Not applicable	Not applicable	Coatings usually not recoverable	Low-cost linings for Al blocks
Heat and corrosion resistant materials and coatings	Exhaust system components	Low-cost, high-volume capability for coatings	High-temperature oxidation and corrosion resistance High durability Good formability	Galvanic corrosion		Not a problem for bulk materials Coatings usually not recoverable	Low-cost replacement for 409 stainless
Catalyst systems	Emission control systems	Low-cost, high-volume capability	Non-noble metal High resistance to aging at elevated temperatures Low susceptibility to poisoning	Not applicable	Not applicable	Need higher-yield process for nobel-metal catalyst	Lower cost Avoid use of critical material

4

Materials Research Agenda for the Civil Aircraft Industry

General and specific research opportunities were determined for the civil aircraft industry using the HSCT (high-speed civil transport) as a basis for analysis. Advanced-materials developments within the context of military aircraft are also occasionally discussed in this chapter, because much of the advanced work is done in this area. Within classes of materials-matrix composites (e.g., polymer, metal, and ceramic), there are a variety of specific materials that could be listed. In general, these specific systems were not listed because the system of choice is not currently known. In the few cases where a specific system is favored, it has been identified and discussed.

NEED FOR MATERIALS-SYSTEMS APPROACH

Innovative materials research and engineering is essential to achieve the high-strength, heat-resistant, lightweight structures required in advanced subsonic and supersonic aircraft. However, as discussed in Chapters 1 and 2, the drivers for technology implementation are primarily economic, not scientific. The barriers to the introduction of new materials include their unusual characteristics that may demand new design methods, the absence of an industrial base to supply the potential need (production applications require production material sources), their cost, and the learning curve necessary to establish their life-cycle characteristics.

Despite the conservative nature of the civil aircraft industry, new materials have been introduced, as demonstrated in applications during the past 20 years. Such materials include graphite-epoxy composites, aluminum-lithium alloys, engineering microtextured materials, and single-crystal turbine blades. These efforts have required teaming relationships among inventors, suppliers, and users. In terms of application, a phased approach has been shown to work best. However, if advanced materials are to be successfully introduced, a more comprehensive materials-system approach must be developed that incorporates materials modeling and processing considerations, and that allows designers to interact even more closely with materials developers to ensure the proper application of new materials.

Materials Processing

Processing and fabrication play critical roles in the utilization of materials. There are also clear opportunities for research on processing in all categories of advanced materials. Indeed, the properties of the advanced material-system candidates are defined by the processes used in their manufacture. Changes in processes can redefine or open new avenues of materials advances as has happened through the application of rapid solidification and melt-spray technologies.

No advanced material will be used, no matter how desirable its properties, if processing and manufacture cannot be performed efficiently and economically. Less than 20 percent of product cost is attributable to design, development, and analysis in a successful aircraft program, while more than 60 percent of the cost is due to manufacturing. There is currently some disconnect between materials, design, and manufacturing operations that together are charged with providing reproducible, cost-effective products. To resolve these disconnects, processing considerations must be included early in the design cycle and production planning of new aircraft.

Modeling of Materials Systems

Another cost and time savings approach that offers potential within the next 20 years to reduce significantly the cycle time required for the introduction of new materials is the use of high-speed computational analysis that has been experimentally validated. One could envision the use of expert systems to help the designer choose appropriate materials and processing techniques for the production of aircraft components.

MATERIALS RESEARCH NEEDS FOR AIRCRAFT AIRFRAMES AND ENGINES

The materials requirements of the airframe and engine systems of aircraft are sufficiently distinct to permit them to be discussed separately. Despite this separation, there are two unifying themes. The first is the need to focus on the mission requirement of future aircraft systems. By understanding customer requirements, materials solutions that will contribute to the mission requirement can be better devised. A second theme is addressing these goals through a team approach.

Anisotropic materials will increasingly become the construction materials of tomorrow's products. This is especially the case in the aircraft industry, where many of the candidate materials systems are composites. Increasing numbers of engineers are required who are properly educated to respond to the problems associated with the synthesis of such materials, their long-term thermostructural and thermochemical stabilities, their design, and their application. Because of the special challenge of the application of materials at extreme temperatures, specialists with expertise in high-temperature thermochemistry and the synthesis of materials for such environments will be required.

Materials for Airframes

In modern, large civil aircraft, aluminum still provides approximately 75–80 percent by weight of the structural materials. Composites have not made the advances into primary structures of civil aircraft that were anticipated 20 years ago, predominantly because of the higher cost of manufacture, the lack of a design base, and the absence of a generally accepted life-prediction methodology. The projections in materials applications in subsonic commercial airplanes are shown in Figure 4-1. Greater progress with composite materials has been made in military aircraft. For example, composites accounted for approximately 50 percent of the structural weight of the prototype advanced tactical fighter (F-22) built by a team from Lockheed and Boeing (Peterson, 1991). The aircraft is projected to contain 35 to 40 percent composites when it goes into production during the latter part of this decade.

The structural materials requirements for the Mach 2.4 HSCT airplane would require materials that could withstand long-term operation at 350°F and very short-term operation at 400°F. However, decreasing the speed from Mach 2.4 to 2.0 has a large effect in reducing surface temperature requirements. At the lower speed, the airplane would need materials able to survive 220°F long-term and 275°F for very short-term exposures. Over the service lifetime of 25 years, the materials would be subjected to some 35,000 thermal cycles.

Materials Candidates

The candidate polymeric composites that can survive the conditions of a Mach 2.4 HSCT airplane for certain structural applications include the carbon-fiber reinforced thermoplastics and thermosets. Cyanate esters and toughened bismaleimides are the currently favored matrices. Polyimide systems offer the requisite temperature capability, but their application is seriously limited by their processibility. Candidate metal systems are more thermally resistant; powder metallurgy aluminum alloys and the alloys of titanium are the most likely candidates. Selective use of aluminum and titanium-base metal-matrix composites may be required, but applications could be limited because of high cost. Currently, for certain small-size components, ceramic-matrix composites are also successfully competing with polymer-matrix composites at temperatures of 600°F.

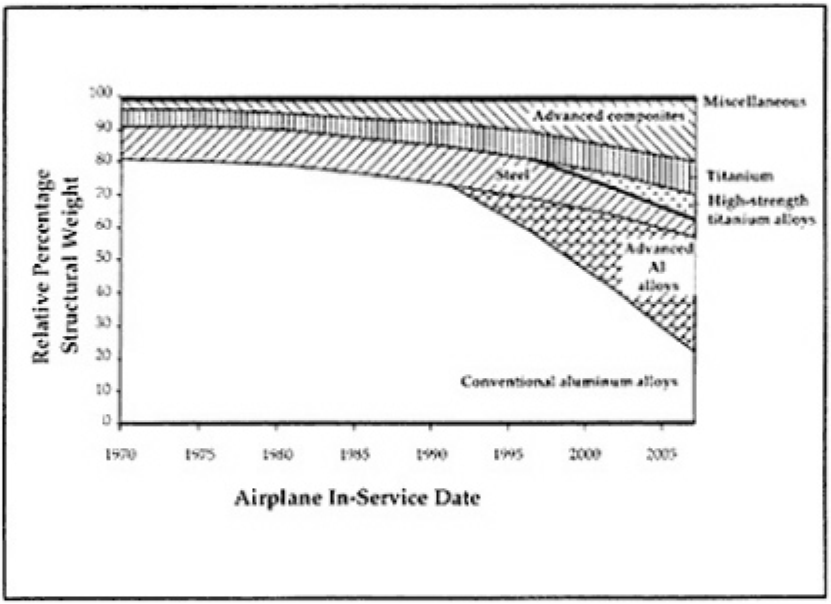


FIGURE 4-1: Material weight-distribution projections for subsonic commercial airplanes (Source: Boeing Commercial Airplane Group).

As suggested in Figure 4-2, the takeoff gross weight favors applications of polymeric composites; however, technical and manufacturing uncertainties prevent the elimination of the metal-alloy candidates. Detailed design considerations are required to rank materials and determine where research should be focused.

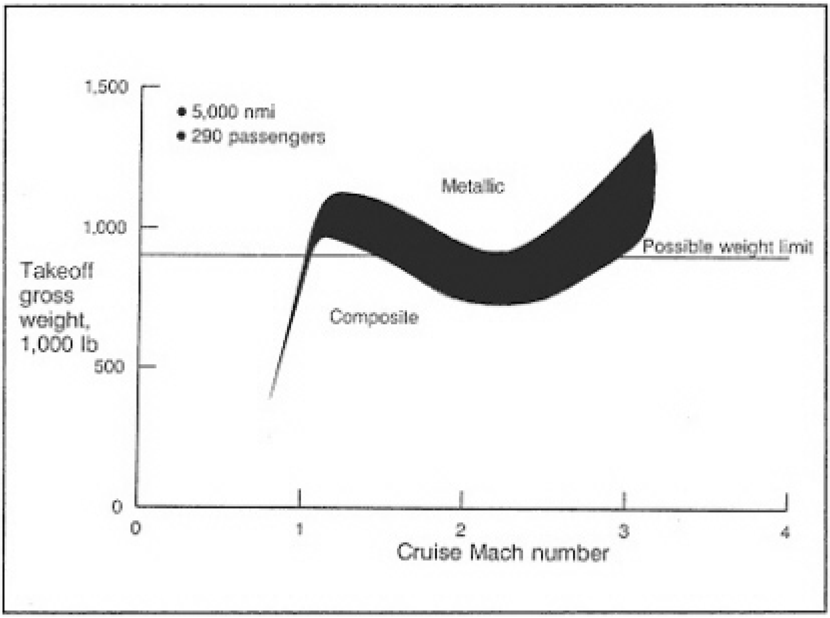


FIGURE 4-2: Airplane size projections for the HSCT (Source: Boeing Commercial Airplane Group).

Joining

The ability to achieve lighter-weight and more fatigue-resistant aircraft structures by adhesive bonding in place of riveting was convincingly demonstrated in the Primary Adhesively Bonded Structures Technology program, conducted by McDonnell Douglas for the Air Force (Hart-Smith, 1981). For successful application, the system for adhesive bonding must be durable in the thermal and chemical environment to which it is exposed. Strong, structural adhesives that are suitable for the majority of the aluminum structures of subsonic aircraft have been identified. Systems with greater thermal capability, as required in supersonic aircraft, compromise bond strengths at lower temperatures. Improved processing methods and adhesive systems are required for the metals and composites being considered for supersonic aircraft.

A chance to change radically the approach to the construction of aircraft is also provided by the application of welding as a replacement to riveted or bonded lapped joints. Such a change should lessen the weight of a metal airframe and improve the attractiveness of metal constructs versus polymer composites. While the current high-strength (e.g., 2024 and 7075) aluminum alloys used for skins are difficult to weld and have demonstrated poor joint efficiency, some of the newer lithium-containing aluminum alloys are weldable. Furthermore, the titanium alloys suitable for airframes of high-speed aircraft are quite weldable. However, the benefits of welding would be lost if additional material was necessary due to limitations imposed by the welding process. Therefore, the committee recommends focused research to address the technical problems, such as residual stress, joint efficiency and reliability, fatigue characteristics, and quality assurance, associated with the application of welding to advanced materials for airframes.

Interface Science

Another associated research opportunity is that of interface science. This is specifically identified since many of the candidate aircraft materials systems are composites. The opportunities of system improvements through adjustments that modify the nature of the interface between the reinforcing phase and the host matrix are immense. Application requires a high degree of thermochemical stability of such engineered microstructures.

Materials for Aircraft Engines

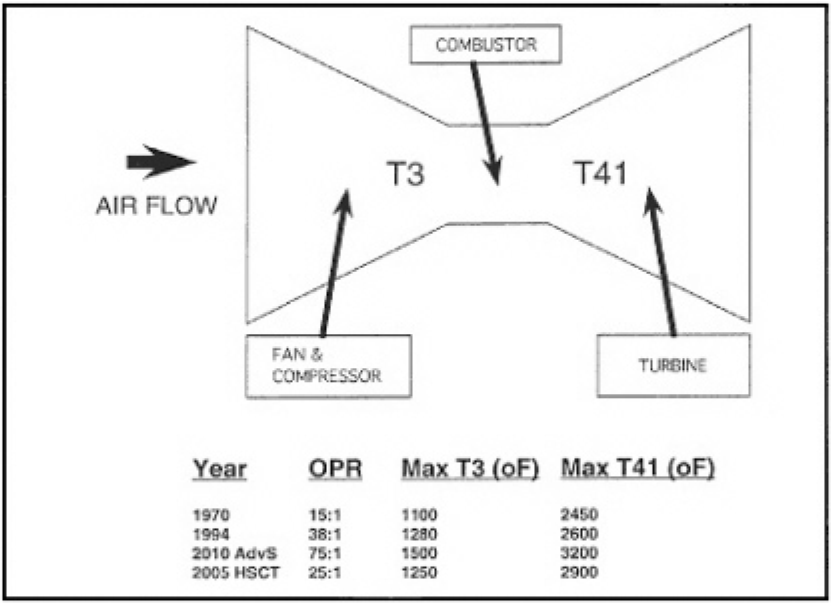
In considering future materials needs for civil aircraft engines, the customer requirements for the first decade of the next century and the leading edge technologies currently being tested by the defense industry must be examined. There will be thrust-improvement derivatives of current advanced engines for both military and subsonic civil aircraft. In addition to the powerplant for the twenty-first century air-superiority fighter, a new high-performance engine for the Navy's A-X aircraft may be developed. An advanced (ultra high bypass) subsonic engine is also anticipated for introduction by about 2010 (Williams, 1991).

By examining such system opportunities, the demands on high-temperature structural materials become apparent as suggested by Figure 4-3. Systems for subsonic aircraft have increased and will continue to increase their operating pressure ratios and their operating temperatures at the rear of the compressor (T3) and at the entry to the turbine (T41). The operational temperatures for rear-stage compressor components and first-stage turbine components of the HSCT are also indicated.

The materials technology required to improve engine efficiency can be summarized as follows:

- Thrust growth in existing engines can be achieved by the use of higher cycle temperatures (T3 and T41), which in turn requires materials with higher temperature capabilities.
- Improvements in the thrust-specific fuel consumption are sought through reduced cooling flow and higher thermal efficiency that directly translates into a requirement for higher-temperature-capability materials.
- Weight reductions that improve thrust to weight of existing or proposed engines can be sought through materials with superior strength-to-weight characteristics.
- Improved value materials that display lower overall life-cycle cost help to define an improved engine; these costs relate not only

to the first cost but also to such issues as the durability of the material and its ability to be repaired.



Year	OPR	Max T3 (oF)	Max T41 (oF)
1970	15:1	1100	2450
1994	38:1	1280	2600
2010 AdvS	75:1	1500	3200
2005 HSCT	25:1	1250	2900

FIGURE 4-3: Applications for high-temperature structural materials for aircraft engines (Source: Williams, 1991).

Table 4-1 lists the material requirements for aircraft engines. This tabular summary progresses from advanced subsonic to military demonstrator to the HSCT engines, and from work that is evolutionary in nature and amenable to engineering program approaches through a set of goals that are a radical departure from industry experience. The latter goals require a suitably directed, highly speculative program of materials synthesis and development that might properly be sponsored on an industry-wide basis. The complexity of the materials innovations required for the HSCT engine will demand the attention of the most experienced and creative people in the profession, and even so, the outcome is uncertain. Worthy of special mention are the ceramic-matrix composites. These composites may address certain of the requirements for materials that must operate in the medium-to-high temperature range, from 600 to 2600+°F. At the lower range of temperature, such materials may be competitive with the fiber-reinforced, polyimide-matrix composites, while at the upper range they compete with the capability offered by carbon-carbon composites.

TABLE 4-1: Material Requirements for Advanced Aircraft Engines.

Advanced Subsonic
• Lightweight fan materials
• High power gearboxes: bearings, gears, lubricants
• 1500°F disk materials
• Higher-temperature turbine blades
• Thermal barrier coatings
• Better tip-sealing systems
Military Demonstrator
• >700°F polymer-matrix composites for casing and static structures
• Titanium aluminide compressor blades
• Ceramic bearings
• Dry lubricants
• Metal-matrix-composite disks
• Lightweight, high-temperature turbine blades
• Ceramic-matrix-composite turbine blades
• Ceramic-matrix-composite exhaust parts
High-Speed Civil Transport
• Combustor: Ceramic-matrix composite for 2600–3000°F needs and high thermal conductivity to meet NO_x requirements
• Exhaust nozzle: Major part of system weight; intermetallic-matrix composites and acoustic absorption required

In addition to these requirements that call for revolutionary materials for the HSCT engine, incremental developments must continue to support the upgrade of existing engines that are primarily dependent upon metals technology. Examples of such incremental approaches are modifications of nickel alloys to provide lower cost; columnar-grained turbine blades with superior oxidation resistance, single-crystal nickel-base alloys for air-cooled turbine-blade applications; dual-alloy turbine disks to permit growth in T3 and T41 temperatures; fine-grained and thin-walled castings for cost and performance benefits; and thermal barrier coatings for life extension and T41 growth. For select applications where thermal conductivity is important, as in turbine disks, metal-matrix composites may also provide useful solutions.

Process-development activities are quality and cost driven. Utilization and improvement of process controls that reduce the requirement for nondestructive evaluation are two such activities. Other examples are clean melting by plasma-arc and electron-beam processes, nickel-base forging billet preparation by spray deposition, and automated ply lay-up for polymer-matrix composites.

The increasing emphasis on using composites for solutions to the material requirements of advanced engines is shown in Figure 4-4. Advanced materials are viewed by domestic gas-turbine manufacturers as key technology discriminators. Failure by the U.S. commercial aircraft industry to achieve preeminence in this area would put the industry's competitive advantage at risk.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

Materials development must be part of a comprehensive systems approach. Materials developers and designers must interact closely over a range of activities, including incorporation of processing considerations into the design process to mitigate the disconnects that occur during materials selection, design, and manufacture; greater emphasis on processing research for all categories of advanced materials to redefine or open new avenues of materials development; and development of materials-selection expert systems to help designers select appropriate materials and processing techniques for components.

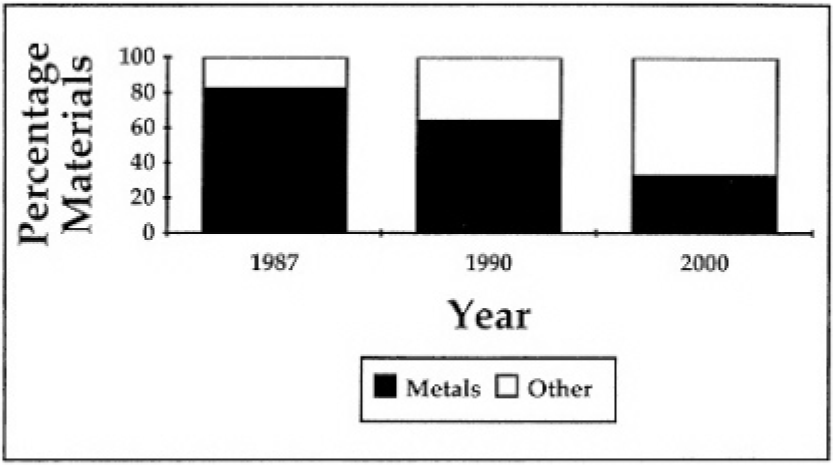


FIGURE 4-4: Engine-materials development activity trends showing increasing emphasis on composites (Williams, 1991).

Aluminum still accounts for 75–80 percent by weight of the structural materials in modern, large civil aircraft. To remain competitive, new advanced materials and techniques must be developed for airframes:

- Polymeric composites are prime candidates for airframe construction. Carbon-fiber reinforced thermoplastics and thermosets, involving the cyanate esters or toughened bismaleimides, are currently favored systems. Composite-research opportunities exist in the areas of (1) long-term thermostructural and thermochemical stabilization, synthesis, design, and application of anisotropic materials and (2) interface modifications between the reinforcing phase and the host matrix.

- The candidate, high-temperature metal systems are the (P/M) aluminum alloys and titanium alloys; selective use of aluminum-base and titanium-base metal-matrix composites may be warranted.
- Improved processing methods and systems for the bonding of metals and composites are needed. For instance, the replacement of riveting by welding in airframes requires further research of the technical problems of residual stress, joint efficiency and reliability, fatigue characteristics, and quality assurance. Candidate materials are the weldable lithium-containing aluminum alloys and the titanium alloys.

The materials research opportunities for aircraft engines are the development of materials with higher-temperature capabilities and thermal efficiency to withstand higher cycle temperatures and reduced cooling flow, superior strength-to-weight characteristics to permit weight reductions, and improved value to reduce overall life-cycle cost. The incremental research opportunities include the development of lower-cost nickel alloys, columnar grained turbine-blades with superior oxidation resistance, single-crystal nickel-base alloys for air-cooled turbine-blade applications, dual-alloy turbine disks for higher temperatures, fine-grained and thin-walled castings for cost and performance benefits, and thermal barrier coatings for life extension.

The ceramic-matrix composites offer a potential for revolutionary changes in propulsion systems. Fiber-reinforced ceramic-matrix composites potentially address a broad range of application temperatures: 600 to 2600+°F. Means to reinforce the ceramic matrices with fiber for higher temperatures is especially challenging, as is the approach to low-cost processing. The benefits afforded by these systems appear to justify the risk associated in their development.

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Appendix A: Workshop Attendees

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Appendix B:

Biographical Sketches of Committee Members

BERNARD H. KEAR is Chairman of the Department of Mechanics and Materials Science and Director of the Center for Materials Synthesis, College of Engineering, Rutgers University. Previously, he was a senior consulting scientist at Pratt & Whitney and science advisor to Exxon Research and Engineering Company. He is the immediate past chairman of the National Materials Advisory Board and a member of the National Academy of Engineering.

ARDEN L. BEMENT, JR. is Basil S. Turner Distinguished Professor of Engineering, School of Materials Engineering, Purdue University, West Lafayette, Indiana. He was previously Vice President of Technical Resources at TRW, Incorporated, Deputy Undersecretary of Defense for Research and Advanced Technologies, and Director of the Office of Material Science at DARPA. He received his E.Met. from Colorado School of Mines, M.S. from University of Idaho, and Ph.D. in metallurgical engineering for the University of Michigan. He is chairman of the Commission on Engineering and Technical Systems of the NRC, former chairman of the National Materials Advisory Board, and a member of the National Academy of Engineering.

I. MELVIN BERNSTEIN is vice president for Arts, Science, and Technology at Tufts University. He was previously chancellor and senior vice president of the Illinois Institute of Technology. He received his B.S., M.S., and Ph.D. in metallurgy from Columbia University. He is a member of the National Materials Advisory Board.

PETER CANNON is managing partner of VRE, a private consulting firm. He was previously President of Conductus and Vice-President for Research at Rockwell International Corporation. He received his B.Sc. in Mathematics and Chemistry and Ph.D. in Physical Sciences from the University of London.

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