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Aluminum R&D for Automotive Uses And the Department of Energy's Role

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EXECUTIVE SUMMARY

The use of aluminum in automotive applications is expanding. Aluminum offers a lower-weight alternative to steel, potentially increasing the efficiency of vehicles. However, the application of aluminum has been only in select areas of use, most notably cast aluminum in the engine, transmission, and wheels. Other areas offer the potential for growth that could significantly expand the amount of aluminum used in vehicles.

Cost is the main barrier to increased aluminum use. Related to cost are aluminum production technologies that are not yet advanced enough to produce aluminum components at low enough price points for aluminum to compete with traditional automotive materials. Today's technologies require higher-priced alloys to be used for the components (e.g., closure panels), or have higher costs for needed processes (e.g., welding). In addition, new designs (e.g., spaceframes) are not well established for widespread use.

R&D efforts are continuing to close these gaps. The U.S. Department of Energy (DOE) is helping to fund certain R&D projects that could provide breakthroughs in lowering costs for aluminum. This paper describes the current state of aluminum applications in vehicles, including its market penetration and opportunities. It also examines the cost structure of aluminum—from mining to final component use. By examining these factors, an evaluation of whether current aluminum technology is mature enough for specific applications is made. Each major aluminum processing step is then reviewed to identify major cost or technology barriers as well as R&D needed to respond to those barriers. For each step, the report provides a discussion of DOE's programmatic role in reducing cost and technological barriers and DOE's Light Weight Materials program support for the overall R&D needs in the industry.

The evaluation embodied in this report finds that aluminum has successfully penetrated the automotive market, largely (>75%) in the form of castings. Aluminum sheet of the proper alloy is still too expensive to penetrate significantly except for components where lower weight has extra value (e.g., large hoods or deck lids). The cost of auto body sheet averages above $1.30/lb, 30% above what the auto industry has said is required for economic competitiveness. Further research is needed to either lower the cost of the alloys currently used for body sheet, or to develop methods to use less expensive alloys. Joining technologies need to be improved to lower their cost while improving quality. Extruded components have potential but will make the most significant contribution if spaceframe designs are developed for high-volume automobile markets. Aluminum has the potential to significantly reduce the weight of vehicles, improving fuel efficiency while maintaining other desirable attributes. Federally funded research contributes to this goal.

1. INTRODUCTION AND OVERVIEW

The use of aluminum in automotive applications is expanding. Aluminum offers a lower-weight alternative to steel, potentially increasing the efficiency of vehicles. Efficiency gains can be used to lower the amount of energy needed for transportation, reducing the emissions while improving the energy security of the country. However, the application of aluminum in vehicles has been largely in select components, most notably as cast aluminum in the engine, transmission, and wheels. These areas still have large opportunities for penetration and other areas offer the potential for growth. Together, these opportunities could significantly expand the amount of aluminum used in vehicles.

With higher efficiencies and lower emissions among the goals of the automotive industry and federal government, programs have been established to conduct research on using more aluminum in vehicles. The Partnership for a New Generation of Vehicles (PNGV) provides the opportunity for manufacturers and the government to conduct joint research projects in creating aluminum-intensive vehicles that can achieve three times the mileage of current models.

Cost is the main barrier to increased aluminum use. Automotive manufacturers are very sensitive to the cost of components and will only adopt higher-cost products if the value they add compensate for the cost. Related to cost are aluminum production technologies that are not yet advanced enough to produce aluminum components at low enough price points or at sufficient quality for aluminum to compete with traditional automotive materials. Today’s technologies require higher-priced alloys to be used for the components (e.g., closure panels), or have higher costs for needed processes (e.g., welding). In addition, new designs (e.g., spaceframes) are not well established for widespread use.

R&D efforts are underway to close these gaps. The U.S. Department of Energy (DOE) is helping to fund certain R&D projects that could provide breakthroughs in lowering costs for aluminum. The Office of Lightweight Materials (LWM) sponsors research in a variety of areas concerning aluminum and aluminum component manufacturing.

In Section 2, this paper describes the current state of aluminum applications in vehicles, including its market penetration and the material form. Aluminum use is broken down both by component and by material form. Section 3 describes the potential increase in automotive aluminum use. Section 4 examines the cost structure of aluminum—from mining to final component use. By examining these factors, an evaluation of whether current aluminum technology is mature enough for specific applications is made. In Section 5, each major aluminum processing step is reviewed to identify major cost or technology barriers as well as R&D needed to respond to those barriers. For each step, the report provides a discussion of DOE’s programmatic role in reducing cost and technological barriers and DOE’s Light Weight Materials program support for the overall R&D needs in the industry. Section 6 provides the overall conclusions of the report.

2. CURRENT STATUS OF ALUMINUM IN VEHICLES

The use of aluminum has increased greatly over the years, with estimates rising from 50 lb/vehicle in 1960 to 250 lb/vehicle in 1999 (Ducker 1998). This amount varies depending on the type of vehicle, as shown in Figure 1. In 1999, for the first time, the aluminum content of light trucks (including pick-ups, mini-vans, and sport utility vehicles) is projected to be higher than aluminum content in passenger cars. General Motors is increasing the content in several of their large pickups, sport utility vehicles (SUVs), and luxury vehicles. Chrysler has greatly increased the average aluminum content in their passenger vehicles, but actually decreased it in their light truck category, as the mix of minivans, pickups, and SUVs changes.

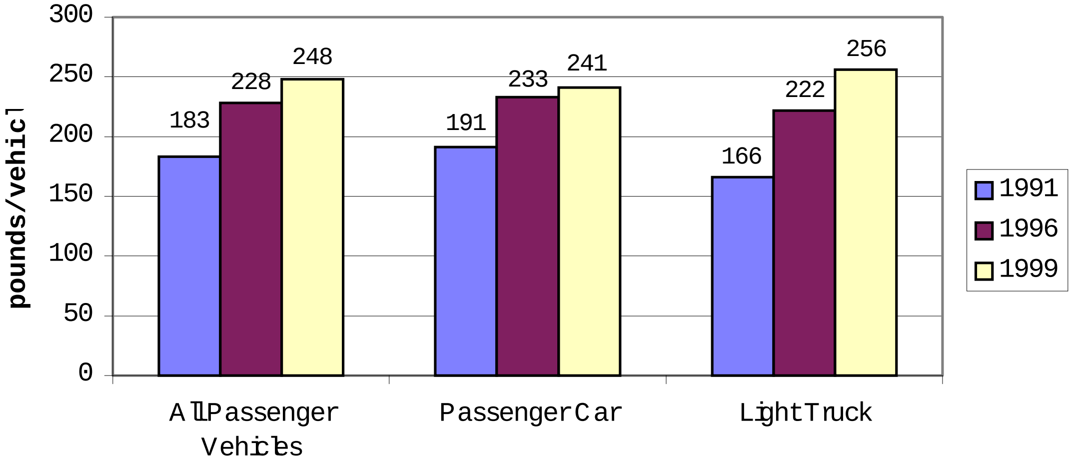

Figure 1. Growth in aluminum content per North American vehicle (Ducker 1998)

2.1 Aluminum Use by Component

Aluminum is used in many vehicle components, but a few components account for the majority of the aluminum now in use. Engines, transmissions, heat exchangers, and wheels represent over 83% of the aluminum currently used in vehicles in North America (Figure 2). Engines can be further divided into components such as the engine block, pistons, and intake manifold.

Figure 2 shows current aluminum use by component but does not show the potential for expansion that exists for these different components. Figure 3 shows the penetration of aluminum into various components for the years 1996 and 1999. These penetration rates represent the percentage of the total market for a particular component that was (1996) or is (1999) produced in aluminum. Those components with low penetration rates offer greater opportunity for expansion of aluminum use, unless there are technical limits on their expansion. For example, closure panels currently consume 47 million pounds of aluminum, but this represents only about 2% of the closure panel market. This level is still small, despite a 65% increase in aluminum use in the past three years (Figure 4). Opportunities for further growth are

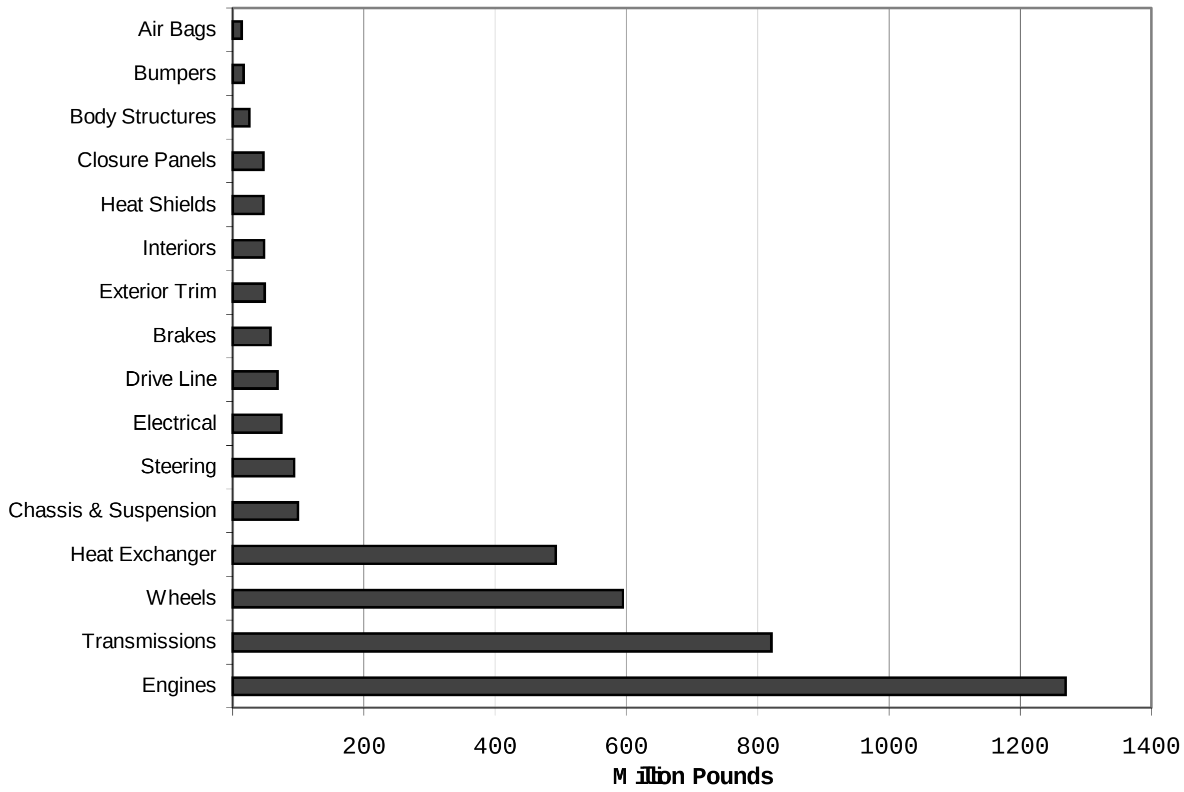

Figure 2. Total aluminum content by system: 1999 (Ducker 1998)

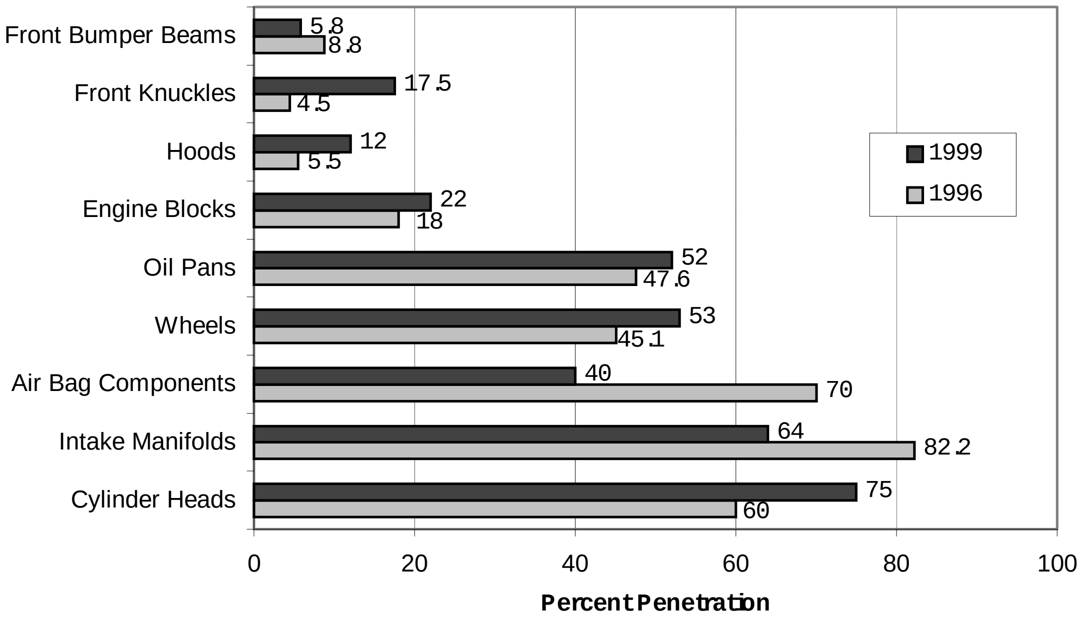

Figure 3. 1996 and 1999 aluminum penetration rates for selected vehicle components (Ducker 1998)

more widespread in this market than in the cylinder head market, which is already at a penetration rate of 75%.

Most of the penetration in closure panels has been in hoods, which still only has a maximum penetration of 8% at Ford. Lower amounts of penetration have occurred in deck lids and liftgates, and practically none has occurred in other panels such as fenders. Market penetration has occurred in components where weight savings are so important that higher costs are tolerated. Such components include hoods, deck lids, and liftgates that the consumer must raise and lower frequently. Costs must be lowered for aluminum to be used in the broader closure panel market.

As can be seen in Figure 3, aluminum has lost some market share for certain components: front bumper beams, air bag components, and intake manifolds. Intake manifolds are changing from aluminum to polymers, nylon, and magnesium. Figure 4 shows the rate of growth for various components. Several components, especially closure panels, steering, and various chassis components, have seen large growth. Since these components have relatively low penetration rates so far, there is a good opportunity for their quantities to continue to grow significantly.

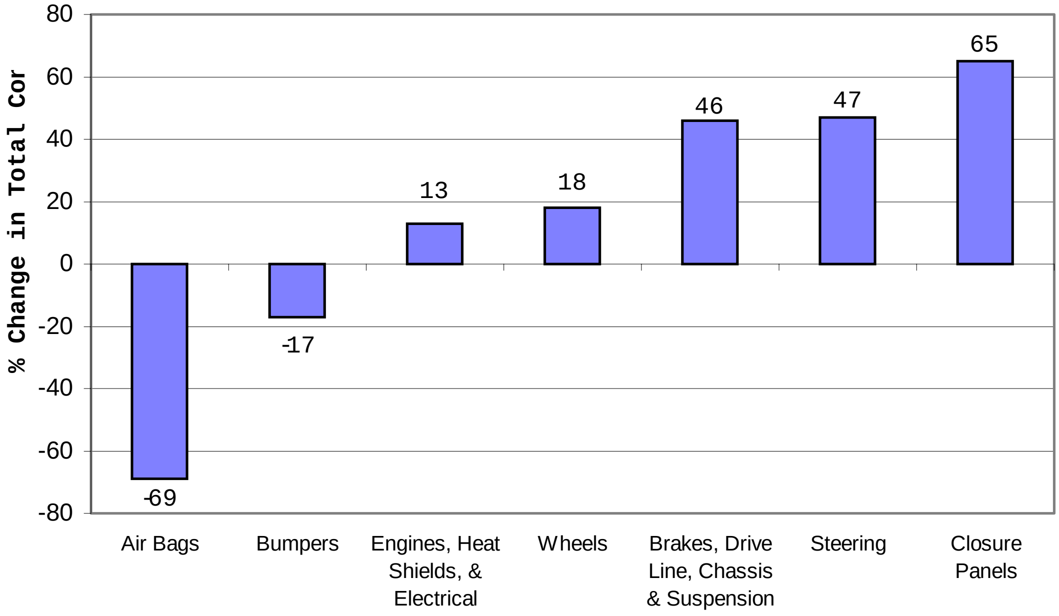

Figure 4. Change in aluminum content between 1996 and 1999 for selected components (Ducker 1998)

The engine contains several major parts that can use aluminum. Table 1 shows the components into whose market aluminum has penetrated. What is surprising is that aluminum has only penetrated 22% of the overall engine block market, although it has grown from only 5% earlier in the 1990s. Foreign manufacturers have been quicker to switch to aluminum. For example, Honda uses aluminum for 100% of their engine blocks.

Some of the major components that could see significant growth in the use of aluminum and contribute greatly to lowering the weight of vehicles are the engine block, closure panels, and chassis components. Over 40% of current vehicles contain aluminum versions of at least one of these components, so manufacturers are becoming more familiar with the products. These each use a different form of aluminum, with different needed characteristics. Research in each of these forms will be helpful in contributing to the use of aluminum in lightweight vehicles.

Table 1. Aluminum Penetration Rates: Selected Engine Components

Engine Component	**Percent of penetration**
Engine cylinder heads	75%
Engine blocks	22%
Engine pistons	100%
Intake manifolds	64%
Starter housings	100%
Engine oil pans	52%

Source: Ducker 1998

2.2 Aluminum Use by Form

The major form of aluminum used in vehicles is cast aluminum. Table 2 shows the percentages of aluminum by form. Castings make up more than 75% of total material used. Castings are used in the major components such as the engine, transmission housing, and wheels. Ninety-eight percent of aluminum engine components are made using cast aluminum, either low pressure permanent mold cast (61%), die cast (27%), or sand cast (10%). There is still the possibility of further use of castings, either in further penetration of the existing components or as new components such as connectors in space frames. Sheet material could grow significantly if used as part of the Body-in-White (BIW) or as separate closure panels. Extrusions could grow with new designs for the BIW, either as spaceframes or in aluminum unibodies.

3. Role of Aluminum in Future Automotive Uses

Aluminum will continue to increase its role in lightweight vehicles. In an evolution of today's vehicles, there will be continued penetration of some of the major components such as engine blocks. In addition, the major manufacturers are conducting research programs that greatly increase the use of aluminum as part of a move to lightweight vehicles. The three domestic manufacturers have participated in the Partnership for a New Generation Vehicle (PNGV). Two of the manufacturers, Ford and DaimlerChrysler, are creating prototype vehicles that greatly increase the use of aluminum as part of their goal to reduce the weight of a vehicle by 40%. The goal of the PNGV program is to develop a mid-size passenger vehicle that achieves 80 miles per gallon (mpg), roughly three times current vehicles' mpg.

The Ford P2000 uses aluminum both for its body-in-white (BIW) and the exterior sheet. The DaimlerChrysler ESX2 also uses aluminum for the BIW but uses plastics for the exterior sheet. Table 3 shows the planned levels of materials for a current vehicle, the P2000 and the ESX2. Overall weight is reduced by roughly 35% but the aluminum content increases by 256% and

Table 2. Aluminum Content by Form (total = 3.8 billion pounds in 1999)

Aluminum Form	Percentage of Total	Major Uses
Die cast	38%	Engine block, transmission, wheels, drive line, exteriors, heat exchanger, interiors, steering, electrical
Low pressure PM cast	34%	Engine block, drive line, brake system, chassis & suspension
Sheet	4%	Heat shield, hubcaps, bumpers, exteriors, interiors, body structure, closure panels
Sand casting	4%	Engine
Brazing sheet	4%	Heat exchanger
Extrusion	3%	Chassis & suspension, bumpers, exteriors, interiors, body structure, steering
Extruded tubing	3%	Drive line, heat exchanger
Fin stock	3%	Heat exchanger
Forged	2%	Drive line, wheels
Squeeze cast	1%	
Other	4%	Brake system, brakes, chassis & suspension, body structure, steering

Source: Ducker 1998

Table 3. Material Use in PNGV Vehicles (lbs.)

Material	1994 Base Vehicle	P2000	ESX2
Plastics	223	270	485
Aluminum	206	733	450
Magnesium	6	86	122
Titanium	0	11	40
Ferrous	2168	490	528
Rubber	138.5	123	148
Glass	96.5	36	70
Lexan	0	30	20
Glass fiber	19	0	60
Carbon Fiber	0	8	24
Lithium	0	30	30
Other	391	193	273
Total Weight	3248	2010	2250

Source: Ducker 1998

118% for the P2000 and the ESX2, respectively. This is because aluminum replaces steel and cast iron in several key components. The P2000 uses an aluminum unibody for its BIW while the ESX2 uses a spaceframe design.

4. COST STRUCTURE OF ALUMINUM

There are a number of steps in the process of manufacturing aluminum components, from raw ore to final fabrication. Each step has costs associated with it. The following section describes the cost components for each.

4.1 Mining and Processing

Aluminum comes from bauxite ore. The sources for bauxite are mainly remote, lesser-developed countries. Table 4 shows the major bauxite producing countries with their market share and typical prices for 1995. The ore prices depend on the quality of the ore, any taxes associated with them, and the ownership of the facilities. Over 78% of bauxite production have alumina facilities associated with them, so that the further processing can be done without extensive transportation costs.

Table 4. Sources and Prices of Bauxite

Country	Market Share	Bauxite Price ($/tonne)	Shipping Cost ($/tonne)
Australia	37%	$17.5	$10.50 to Tacoma
Guinea	16%	$26.30-$28.90	$6.34 to East coast
Jamaica	10%		
Brazil	10%	$21.90	
India	4%		

Source: Thompson 1995

Figure 5 shows the cost components for alumina manufacture, including raw materials, capital, labor, and energy. Figure 6 shows how closely tied are the market prices of alumina and aluminum. Most alumina manufacturing is done outside the United States, although there are facilities in the U.S. Virgin Islands. According to the U.S. Geological Survey:

> Domestic ore, which for many years has accounted for less than 1% of the U.S. requirement for bauxite, was mined by one company from surface mines in Alabama and Georgia; virtually all of it was used in the production of nonmetallurgical products, such as abrasives, chemicals, and refractories. Thus, nearly all bauxite consumed in the United States was imported; of the total, about 95% was converted to alumina. Also, the United States imported about one-half of the alumina it required. Of the total alumina used, about 90% went to primary aluminum smelters and the remainder to nonmetallurgical uses. Annual alumina capacity was 6.2 million tons, with five Bayer refineries in operation at year-end (Plunkert 1999).

The report further states that net imports represented essentially 100% of apparent domestic consumption.

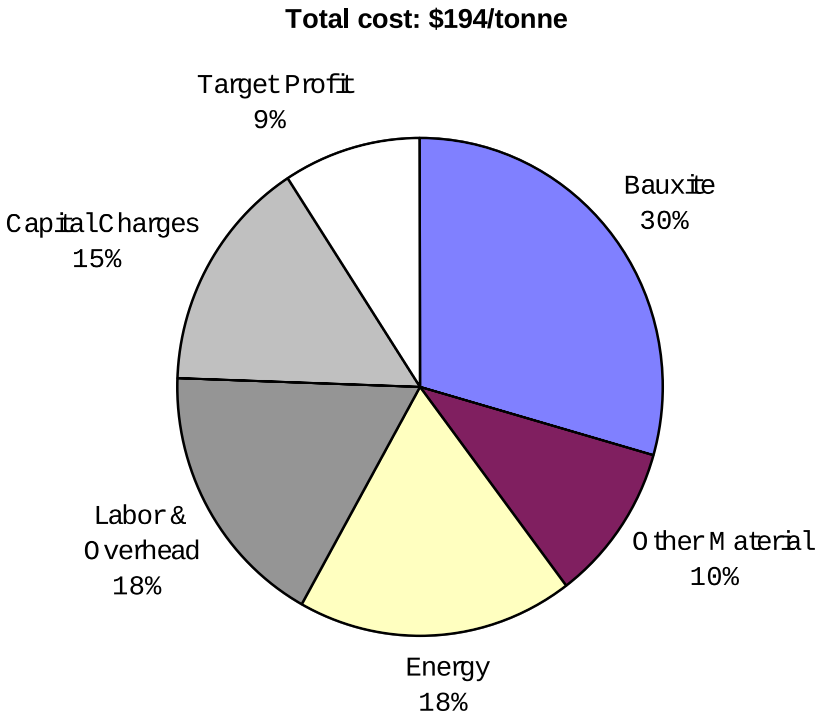

Figure 5. Cost components of alumina (King 1995)

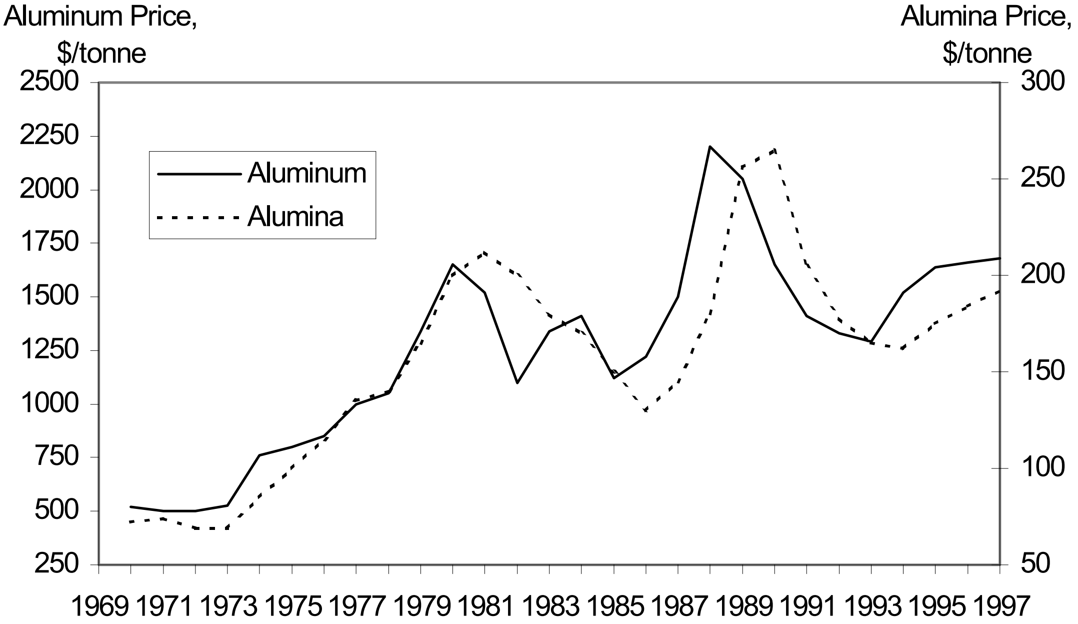

Figure 6. Aluminum and alumina price trends (King 1995)

4.2 Smelting

The United States is still one of the leading producers of primary aluminum, but its market share has declined over the years from 40% in 1960 to only 17% in 1997. Canada is also a major producer, with 11% of the world market in 1997. Mexico however, produces insignificant amounts of primary aluminum. The major companies involved are ALCOA, Kaiser, Reynolds, and Alcan. These are multi-national firms, and individual production facilities are often shared between manufacturers.

Aluminum smelting is a capital- and energy-intensive process. All facilities use the Hall-Heroult process to reduce (remove the oxygen) from alumina to make pure aluminum. This is done by electrolyzing the alumina in a molten salt bath with carbon electrodes. The main costs of smelter operation are shown in Figure 7. It is not clear whether the costs of secondary aluminum will be any lower than that of primary aluminum, when taking into account the cost of collection and separation of aluminum for recycling. The value of aluminum also will be determined to a large extent by the effect of large quantities of aluminum from automobiles on primary and secondary markets and the extent of separation between wrought and cast alloys (discussed more in Section 4.8).

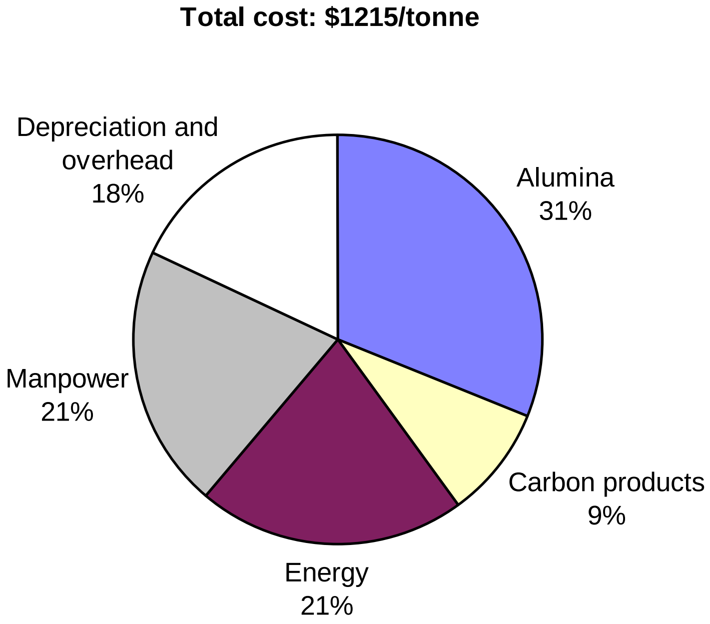

Figure 7. Operational cost of state-of-the-art aluminum smelter (Tessier-duCross 1994)

4.3 Final Form

The cost of the final form is greatly dependent on the form needed, be it cast, stamped, or extruded. Casting and sheet stamping have high setup costs that accentuate the cost of low-volume production. Figure 8 shows one analysis of the cost of final vehicle components on a per pound basis depending on the final form.

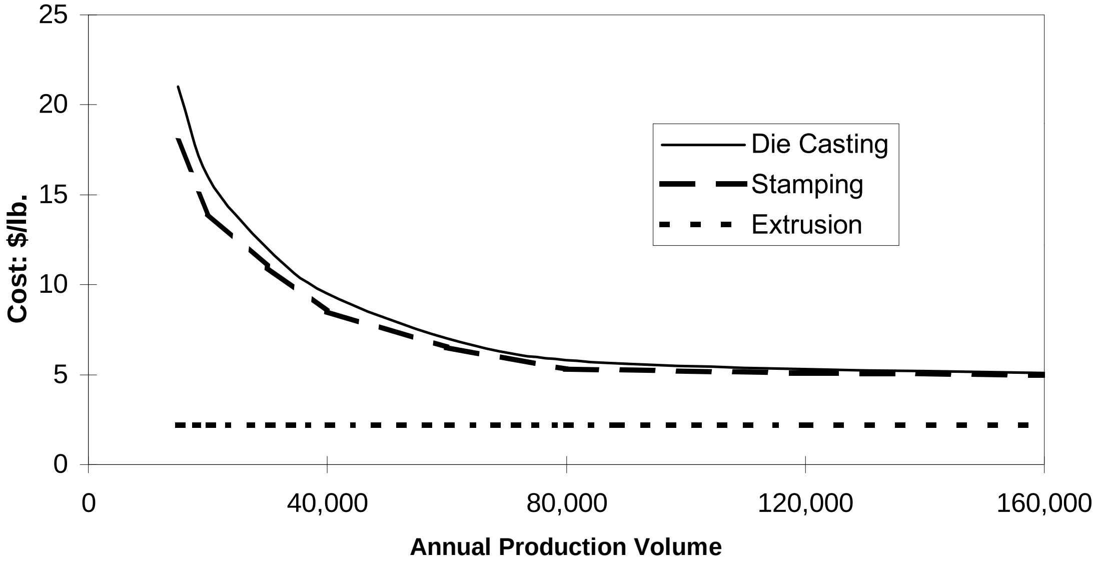

Figure 8. Production cost per pound as a function of volume
(Politos 1995)

4.4 Cast

Casting begins with either primary ingot or molten metal that is transported from the smelter to the cast house. Once there, it is alloyed, filtered, fluxed, and cast into forms suitable for forging, extruding, rolling, or remelting (Malling 1997). These forms can vary from large slabs used for further rolling to sheet, smaller billets or bars that are used for extrusion, or semi-finished forms that only need final shaping for use as components. Casting molds for semi-finished forms can be complex. The cost of casting depends on the form to be cast and the quantity to be made. The cost of molds and setup—up-front costs—can be very high in proportion to material costs at low production volumes. As volume increases, these costs are spread over more parts until variable costs such as material and labor begin to predominate (Figure 8). Casting typically uses lower cost alloys than sheet stamping.

4.5 Stamped Sheet

Aluminum sheet is made by rolling slabs of cast aluminum alloy through a mixture of hot rollers, cold rollers, annealing furnaces, and mills. Sheet manufacture may start with a 2ft.X5ft.X20ft. slab that has its surface ground smooth and then rolled to a thickness of less than 0.08 inch. The number and type of steps depend on the alloy and desired thickness of the final sheet. Some alloys require a final heat treatment to achieve the necessary qualities for use in vehicles. Each step adds additional cost to the final product so minimizing the number of steps is a significant contributor to lowering costs. The aluminum industry's goal is to create sheet that is usable for vehicles at a cost of $1/lb (Aluminum Association, Inc. 1997). Continuous casting technologies are being developed that could greatly reduce the number of subsequent processing steps required, lowering costs.

The cost for auto body sheet has fluctuated over the past years, due in part to changes in the cost of raw material. Figure 9 shows the weighted average cost of aluminum body sheet from 1996 to 1999. Cost of raw material includes not only the virgin aluminum but also alloying elements, reuse of scrap, and losses. Labor costs increased greatly between 1998 and 1999, largely due to increases for North American producers. As can be seen by the graph, costs remain above $1.25/lb on average, although a few producers have costs below this. Although aluminum ingot spot prices dropped as low as 50¢/lb. in 1998, the cost of raw materials (including aluminum and alloying) to sheet producers was above 80¢/lb.

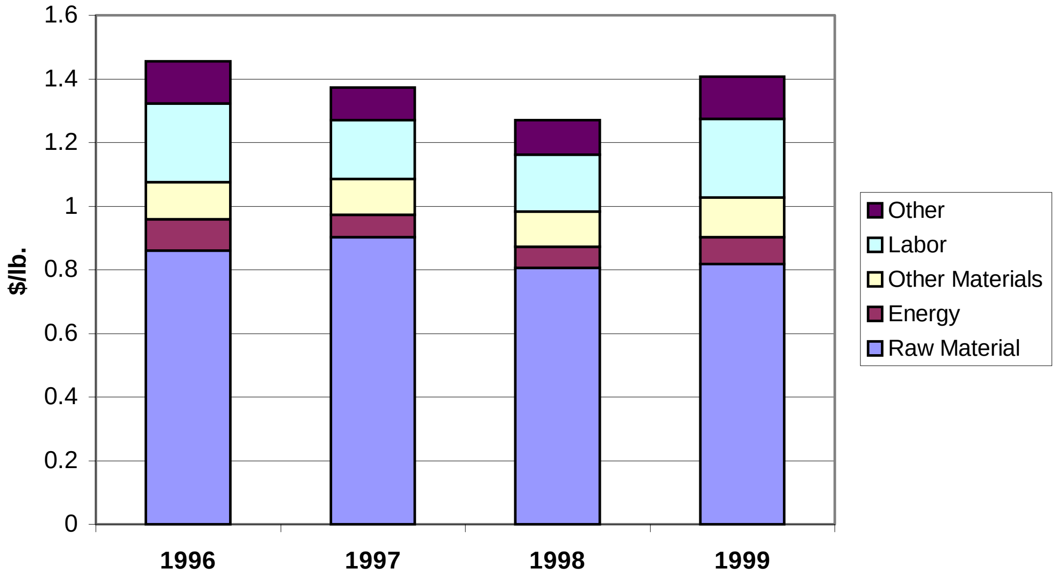

Figure 9. Average cost of aluminum auto body sheet
(CRU 1998)

Stamping then entails significant additional expense, mainly in the cost of tooling, maintenance, and overhead. Material cost represents about one third of the total cost of the stamped part, depending greatly on production volume (Figure 8).

Cost comparisons with steel depend greatly on the part being stamped and volume of parts. If a part requires a high amount of trimming, then the higher material costs of aluminum accentuate the cost penalty. Figure 10 shows a sample cost comparison for a single stamped part made with both aluminum and steel. The higher aluminum cost (material cost) dominates the cost differential. Other production costs are less for aluminum than for steel. Previously mentioned weight factors associated with hoods and decklids will lessen the cost penalty. Two other mechanisms can further reduce the cost differential. Redesigning the part so that the fraction lost to trimming is lessened and yields increase will lower the amount of scrap.

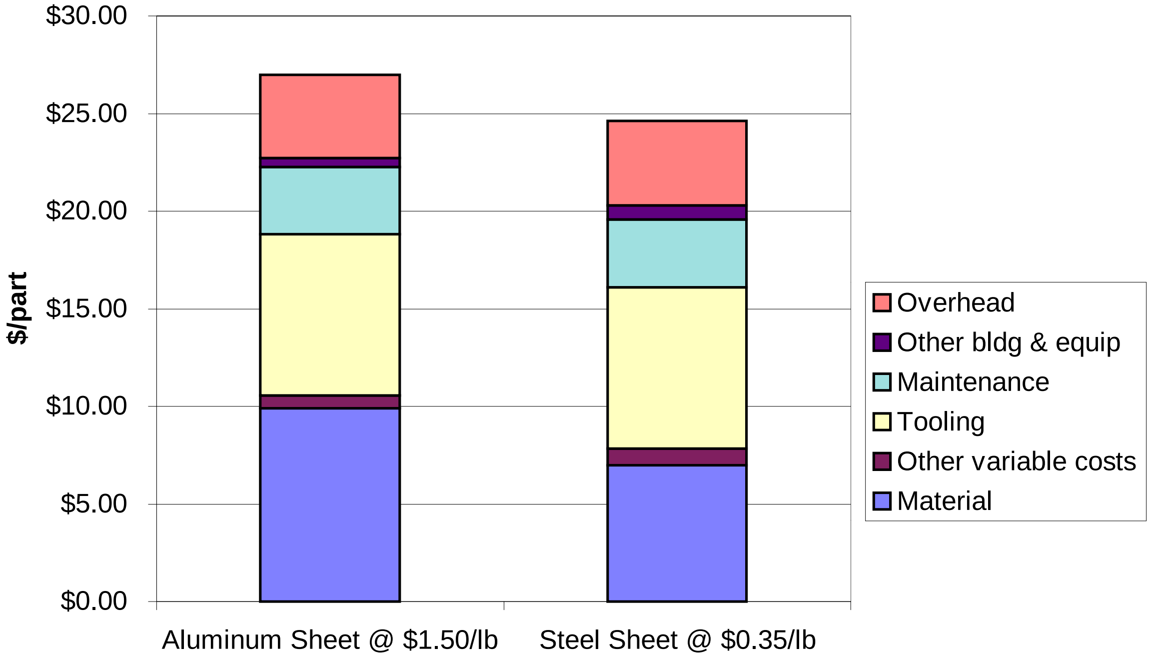

Figure 10. Cost comparison of aluminum and steel part manufacture at volume of 200,000/year (MIT 1997)

4.6 Extrusion

Extrusion involves using large presses to force a billet of heated cast aluminum through a shaped die or dies. Resulting shapes must be relatively simple, either straight or with relatively few bends and with constant cross-section. Because of this relative simplicity, equipment setup costs are lower so that smaller batch sizes do not have considerable penalty (Figure 8). Also, the major dedicated equipment cost is the cost of the dies. The mechanical presses can be used for a wide variety of parts and so their costs can be spread. Materials account for roughly half the cost of an extruded part. The alloy used for the extruded part will greatly influence its cost. Various finishing techniques such as hydroforming (below) can be used to further shape pipes or bars created through extrusion.

Figure 11 shows the cost per pound of an extruded part. The last column shows the raw material and other manufacturing costs. The second column breaks down the raw material (aluminum) cost into its raw material (alumina) and manufacturing components, and the first column shows the breakdown of the alumina costs.

4.7 Assembly

Once components are manufactured, they must be assembled into the complete vehicle. BIW designs can be created using a frame and chassis, unibody, or spaceframe design. Spaceframes offer a potentially large reduction in the number of parts to be joined. The main structural support is carried through extruded parts. These are joined together through use of cast

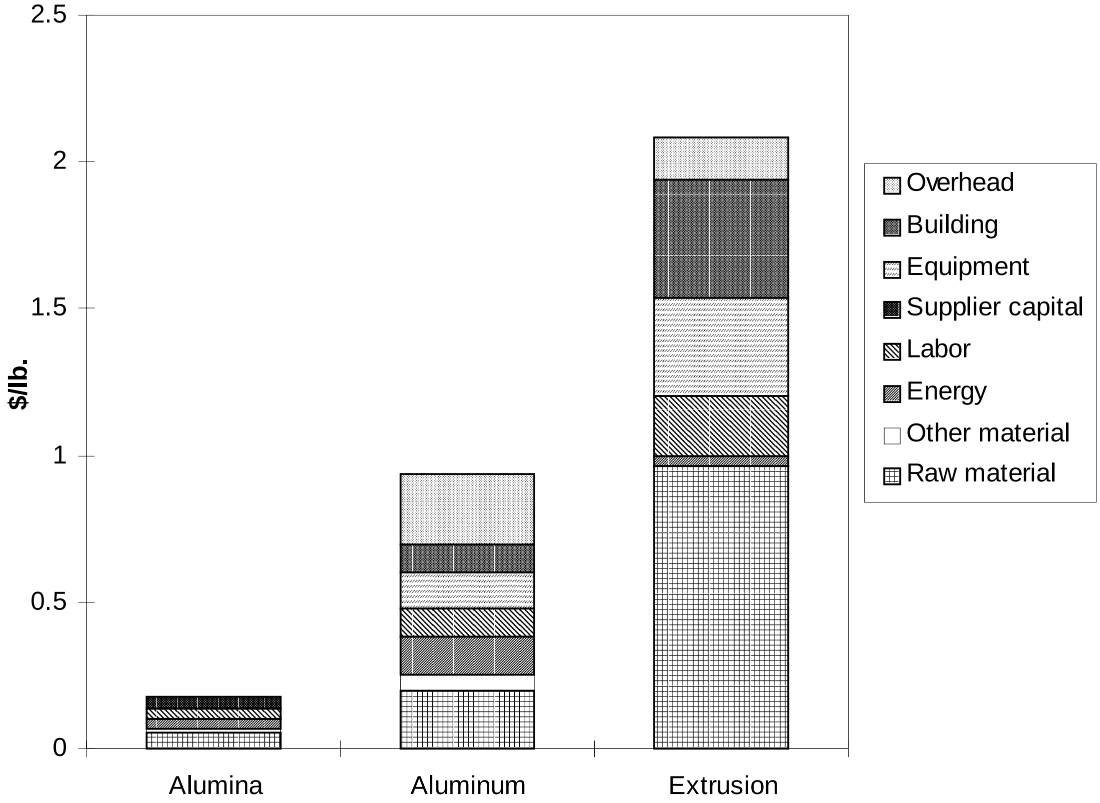

Figure 11. Extrusion cost by category, including raw material

nodes, or by other bonding techniques. Since spot welding is difficult with aluminum, other joining methods such as punch-riveting, welding, and adhesive-bonding are used. Aluminum spaceframes are about 40% lighter than the steel unibodies they replace and are more rigid (Ashley 1994). Unibody design is the most common form for high-production-volume vehicles. Spaceframe design is currently more suitable for low volumes.

Studies comparing the cost of different BIW structures show the impact of production volume and technology used. A 1995 study compares three types of spaceframe designs with aluminum and steel unibody designs (Politos 1995). Steel unibody designs had the lowest cost except at low volumes. At 20,000 units per year, one of the spaceframe designs was lowest cost, but it used techniques that are difficult to expand to higher levels (Figure 12).

4.8 Recycling

One of the strong factors that help make aluminum more affordable for automotive uses is recycling. Aluminum represents 35% to 50% of a vehicle’s total scrap value, despite being only 5% to 10% of the vehicle’s weight (Aluminum Assoc. 1999). Today the recycling rate of automotive aluminum is estimated to be between 85% and 90%, and the product of recycling—secondary foundry alloy castings—constitutes fully 60-70% of the aluminum used in current vehicles. Like ferrous materials, aluminum is recycled at three stages. During manufacture, scrap (or "offal") is recycled either within the automotive industry or back through the aluminum

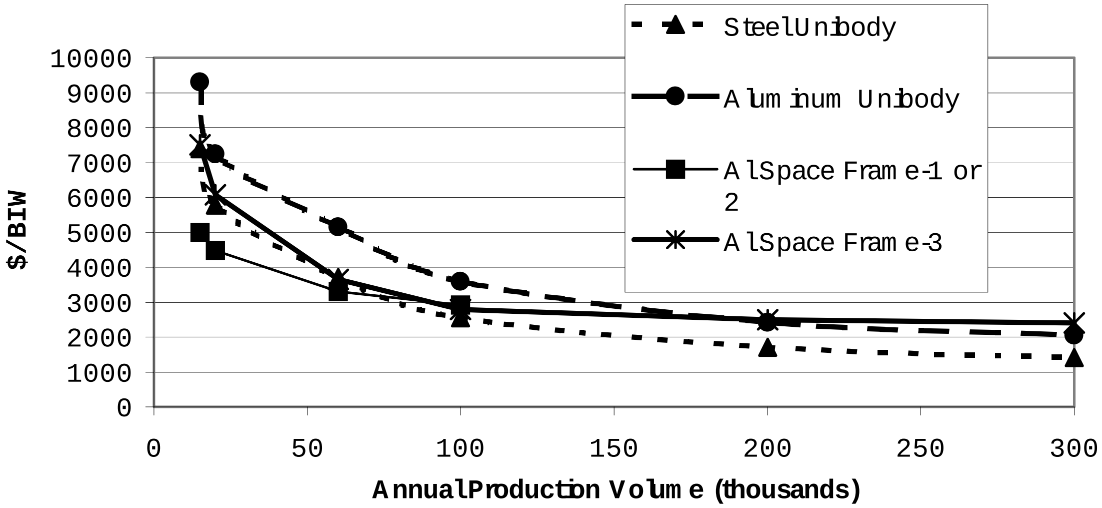

Figure 12. Comparison of BIW cost by production technology and material (Politos 1995)

industry. This recycling lowers the effective cost of aluminum because it creates a higher utilization rate. At the end of life for a vehicle, auto dismantlers remove the useful parts and the easily separated components. The remaining vehicle is then crushed and shredded. Ferrous, non-ferrous metallic, and other materials are separated for either recycling or disposal. Several technologies are used to further separate the aluminum from the other non-ferrous metals, and the resulting mixed alloy scrap is sent back to the aluminum industry. Because casting represents around 80% of aluminum use in vehicles today, and will continue to be a large proportion of aluminum in vehicles in the future, castings should be able to absorb the scrap generated through recycling in the near term. However, as the use of aluminum sheet and other wrought forms of aluminum increases, technologies need to be developed to better separate the various aluminum alloys and wrought vs. cast aluminum.

4.9 Cost Summary

Although aluminum has achieved tremendous growth in the automotive market, it has largely been in specific areas: engine components, powertrain, wheels, and heat exchangers. Further growth is dependent on increasing penetration into the engine block market and new structural components such as the BIW and closure panels. The cost of engine blocks is hampered by the need for and cost of cylinder liners, as well as the need for better information on alloy characteristics. The cost of aluminum autobody sheet is still in the $1.30 range or higher, above the $1/lb that the industry needs for aluminum to become widely cost-competitive. Steel parts are still cheaper than aluminum. Unibody designs are more cost-effective at high volumes than spaceframes, and steel is less expensive with that type of design. Recycling helps to offset the higher cost of aluminum by reducing material costs during manufacture and creating higher value for the scrapped vehicle at the end of life.

5. BARRIERS TO GROWTH AND R&D OPPORTUNITIES

As described above there are a number of opportunities for growth in the use of aluminum. Further penetration of cast aluminum in existing uses, as well as new uses in PNGV-type vehicles will provide continued growth. However, there are barriers to additional penetration of aluminum. These are largely related to the need for lower costs, improved technologies, or better metallurgy. No single breakthrough will be sufficient to make aluminum totally cost-competitive and widely used in vehicle manufacture. Rather, there is a synergy between the different advances that will combine to bring the overall cost down to affordable levels.

Within DOE, most of the R&D focused on automobile materials is in the Office of Transportation Technologies (OTT). In particular, OTT's Office of Advanced Automotive Technologies (OAAT) published a long-range plan for its R&D in the area of lightweight structural materials for body and chassis applications, as well as materials for advanced propulsion systems in automotive applications (DOE 1998). Aluminum is one of the major materials, along with magnesium, titanium, and carbon fiber and metal matrix composites. In addition, an aluminum industry roadmap to enhance the cost-effectiveness of aluminum in automotive applications has been published. It concentrates on the entire process chain of automotive manufacturing, from the production of semi-finished aluminum shapes through the assembly process and finally the recycling of automotive aluminum scrap. It includes crashworthiness and the use of aluminum metal matrix composites (Aluminum Association 1999).

The DOE Office of Industrial Technologies (OIT)—which along with OTT is part of the Energy Efficiency and Renewable Energy Program—works with the aluminum industry to identify and develop improved technologies aimed at reducing the energy consumed in the production of the primary metals. The relevance of OIT's projects to automobiles is mainly in reducing the cost of the primary metals. Research areas funded by OIT are based on a detailed technology roadmap developed through the Industries of the Future Initiative and the Aluminum Association, Inc. on behalf of the aluminum industry (Aluminum Association 1997). Development of advanced anodes and cathodes and processing and recycling of aluminum wastes are some of the areas that currently are being funded to reduce energy consumption, pollution, and production costs of aluminum.

All of DOE's current R&D activities, beyond the primary metal production stage, are currently being funded primarily by the Lightweight Materials (LWM) program of OAAT and are based on its long range R&D plan (DOE 1998). Table 5 lists the 15 specific projects that are funded under seven major research areas. The total budget for these aluminum projects forms a sizeable share of the total LWM budget and aims at satisfying the current critical needs of the industry, particularly sheet and joining. The projects related to aluminum composites have not been considered here.

In the sections below, we discuss the major barriers and the R&D being pursued for each step in the production of finished aluminum components. Each section briefly describes the LWM projects under each major area and their contribution to meeting the overall needs of the industry. Very limited information exists currently on the economic viability or cost-effectiveness of these projects, but this type of evaluation is being planned for some of these

Table 5. Aluminum Projects Currently Funded by the Lightweight Materials Program (project titles)
1. Aluminum Alloy Sheet
a. Low-cost aluminum alloy sheet production
b. Non-heat treatable aluminum alloy body sheet products
2. Aluminum Sheet Forming
a. Advanced forming of aluminum
b. Semi-solid aluminum forming/casting
c. Optimization of extrusion shaping and joining technology for lightweight structures
d. Advanced high volume manufacturing technology validation for lightweight automotive structures
3. Dissimilar Material Joining
a. Adhesive bond durability of structural automotive materials
b. Nondestructive evaluation techniques for on-line inspection of structures with adhesive joints
4. Energy Absorption Models
a. Development of advanced tools for energy management (Crashworthiness study of lightweight aluminum automotive structures)
5. Technology Validation and Assessment
a. Characteristics of aluminum tailored blanks for automotive panels and structures
6. Materials Recycling and Repair
a. Recycling of automotive materials and components
b. Hot crush technology for separating wrought and cast aluminum
7. Cast and Formed Advanced Metals
a. Design and product optimization for cast light metals
b. Rapid tooling for functional prototyping of metal mold processes
c. Die casting and die life extension

Source: US Department of Energy

projects during this year. Other information on these programs is available in the paper "Overview of DOE's Program on Aluminum and Magnesium for Automotive Applications" (Carpenter et al. 1999).

5.1 Primary Aluminum

Cost or technology barriers

Experts at the Technology Roadmap Workshop (Aluminum Association 1997) identified a number of technology barriers to improving the processes used for primary aluminum manufacture. The Bayer process, used to convert bauxite to alumina, has productivity limitations in the chemical processes used. The Hall-Heroult process could be made more efficient with a better understanding of the some of the basic processes, such as anode/cathode technology, bath chemistry, effects of new cell designs, and control of energy losses. Controls and monitoring instrumentation need improvement to better control the steps in the Bayer and Hall-Heroult processes and improve their productivity.

R&D to respond to barriers

Primary aluminum manufacturers are conducting research to reduce the cost and increase the quality of the individual processes. One example is the improvement in anodes and cathodes used during the process. Because much of the initial processing occurs in countries outside the United States, much of the research is being conducted in those countries (e.g., alumina productivity in Australia). Smelting research is concentrating on improving the efficiency of the Hall-Heroult process. The government role in these areas of research is limited because of the competitive market, mature industry, and difficulty in finding solutions.

5.2 Casting

Cost or technology barriers

Cast aluminum parts, while lighter than iron and possessing other desirable qualities, are still too expensive for some applications. Domestic manufacturers continue to use cast iron for most of their engine blocks. Aluminum may be used, but it requires harder cast-iron sleeves for the cylinder walls. This raises the cost of an aluminum block, which may deter its use especially in low-end vehicles where cost reduction is most important.

Engine blocks mainly use a 319 alloy of aluminum while chassis parts use 356 alloy. There are still some issues regarding porosity and castability of 319 that can deter its use. However, powertrain manufacturing is largely done in-house by the big three automakers. They are reluctant to share research in areas that could release proprietary information.

As shown in Figure 8, die casting has large upfront costs that greatly increase per-part costs at low production volumes. Much of the upfront cost is in the development and manufacture of dies to be used. Any efforts to reduce the cost of dies or extend their lives will lower the cost of cast components.

R&D to respond to barriers

Researchers are exploring mechanisms to flame-spray coatings on cylinder walls as an alternative to sleeving. This lowers the cost of manufacture, as well as the weight of the blocks by eliminating the cast iron sleeves. Efforts are underway to extend the lives of dies through development of internal coatings. Also, rapid prototyping of dies will help to reduce costs. Government-funded research in casting has focused on chassis parts that often are manufactured by suppliers to the big three automakers, instead of the automakers themselves. More of the research results are pre-competitive and can be shared with multiple suppliers.

LWM-sponsored projects

LWM sponsors three projects in the area of cast and formed light metals. The objective of the first is to optimize design knowledge and improve product capability for lightweight, high-strength, cast structural components for chassis and interior automotive components. The second project under this category focuses on developing the materials processing and design technologies required to reduce the prototype development time for metal mold processes which is critical to increasing castings' share of new markets. The objective of the last project is to improve the energy efficiency and cost-effectiveness of large-scale automotive aluminum die castings by extending die life and reducing die wear.

5.3 Rolling and Stamping

Cost or technology barriers

The main barrier to further penetration of aluminum in sheet-dependent components is the cost of making sheet that has the right characteristics for these uses. Currently, the alloys that could be used for exterior panels (the 6000 series) require heat-treating and other processes that raise the cost of sheet to between $1.25/lb and $1.50/lb.

R&D to respond to barriers

The industry, with government support, is researching the use of continuous belt casting as a means to reduce the cost of rolling. This could eliminate several of the steps needed in making aluminum sheet. This work is being done on both 6000-series and 5000-series alloys to determine the suitability of different compositions to this technique.

In addition, other work is being done to develop a 5000 series alloy that would perform adequately for exterior surfaces. Proper control of the metallurgy and equipment are needed to gain the desired properties. This alloy, as opposed to the 6000 series alloys, would not require heat-treating.

One way to compensate for higher-cost materials is to lower the amount of material used. One mechanism for lightweighting components is to maintain the volume of material in critical areas of the component but reduce it in others. This can be done by welding several pieces together before they are stamped into the final form. These are called tailor-welded blanks. The technology can be used for aluminum or steel blanks. The Office for the Study of Automotive Transportation (OSAT) at the University of Michigan reports the following:

> Tailored blanks are constructed of two or more blank pieces typically with different properties of steel gages, different metallurgical grades (mild and high strength), or different coatings (bare and galvanized). A traditional body side panel might require five separate sets of dies to make reinforcement parts at critical points. This is replaced by one tailor welded blank that contains all of the metal strengths joined together and only requires one set of dies. The ability to optimally assign the needed steel grade, gage, and coating to the part only where it is needed revolutionizes the traditional design approach. With this flexibility, the number of parts and the shape of the blanks become more efficient and help achieve higher performance, lower cost and lighter weight (Baron and Dickinson 1996).

Recent studies have shown that the economic break-even point for tailor-welded blanks, i.e., the point at which aluminum blanks become competitive with steel sheet, is $1.10/lb. to $1.20/lb. rather than $1/lb (Das 1999). This means that other advances, such as twin-roller casting or use of different alloys, have a greater chance of making aluminum sheet cost-effective in this use.

LWM-sponsored projects – Aluminum sheet production

Two projects are being conducted in the area of aluminum sheet manufacturing. The first project is developing the metallurgy and processes to use continuous-slab, twin-roller casting. This process has been successfully used by industry for the manufacture of products such as can-stock and foil, and it could be adapted to make sheet for closure panels and the BIW. However, the optimum amounts of alloying agents and rolling sizes need to be researched for 6000 and 5000 series alloys that would create suitable sheet stock for automotive uses. The second project is concentrating on developing a 5000 series alloy that would be useful for exterior surfaces.

LWM-sponsored projects – Aluminum sheet forming

Under the sheet forming area, R&D projects are directed at improving the formability of aluminum sheet. The projects explore two advanced processes incorporating improved control methods, i.e., process/press optimization and warm forming. The first of these projects is working to improve the aluminum sheet metal stamping process. It is developing a method to control the flow of metal into a tooling cavity by application of binder load distribution techniques, active beads, and open-loop control. The semi-solid or warm forming of aluminum project aims to develop technology that offers the near net shape capabilities and process economics of die casting but produces components that have mechanical properties exceeding those of permanent mold castings and approaching those of forgings.

LWM-sponsored projects – Technology validation of tailored blanks

Models and analysis are needed to verify technologies that will yield the necessary weight reduction of body and chassis. The only LWM-sponsored project in this area aims to develop a comprehensive forming, performance, and durability database that will allow the automotive designer to optimize weight, structural performance, crashworthiness, and overall cost in the application of aluminum tailored blanks in closure panels and body-in-white structural components. Primary issues that are being addressed by the project include mechanical properties of the welded panels, corrosion behavior, as well as toughness characteristics and fatigue properties of the welded blanks when subjected to typical forming strains and automotive paint bake cycles.

5.4 Extruding

Cost or technology barriers

Because extrusion alone produces only relatively simple parts, it has less widespread application than other production methods. Additional forming can be done on extruded parts to increase their complexity, but at added cost. Nonetheless, extrusion is a widely used technology, whose advantageousness improves in conjunction with a spaceframe BIW. To increase the use of extruded parts, assembly techniques (e.g., spaceframes) that recognize its limitation must be adopted, or new forming techniques (e.g., hydroforming) to create more complex shapes from extruded parts at lower cost must be developed.

R&D to respond to barriers

New techniques for extrusion are being developed that will allow thinner walls, and consequently less weight, while still maintaining adequate overall strength. Component manufacturing and assembly processes will further improve the advantages of extruded aluminum.

Hydroforming forms finished parts from tubular extrusions or sheet. The rough part is placed in a form and high-pressured liquids are forced into its hollow core. This expands the material into the shape of the form. A manufacturer describes the process and the product as follows:

> Tube hydroforming is a pressurized hydraulic forming process used to produce complex shapes in tubular components, typically ranging from three to ten feet long (1m - 3m), and one to six inches in diameter (25mm -150mm). Replacing traditional stamp and weld manufacturing, components produced with tube hydroforming are lighter, stronger, and require fewer pieces. Tube hydroformed parts retain their structural integrity; wall thickness is constant throughout the part. Manufacturers realize substantial cost savings, both in lower tooling costs and lower labor costs. Hydroforming technology is applicable to any industry where complex shapes must be formed with a high degree of precision. Automotive applications include radiator enclosures, space frames, dash assemblies, frame rails, engine cradles and other sub-assemblies (Vari-form 1999).

LWM-sponsored projects – Aluminum sheet hydroforming

Development and demonstration of predictive models for extrusion hydroforming and multi-element joining is the focus of the one LWM-sponsored project in the area of aluminum sheet forming. The project began a year ago with the main objective of promoting the share of aluminum use in automobiles by the increased use of extruded shapes. A hydroforming model has been developed which includes tool closing, tube deformation, and hydroforming itself.

5.5 Joining and Assembly

Cost or technology barriers

A critical problem with aluminum assembly is that joining aluminum requires a different set of technologies and procedures from steel. Because of aluminum's properties, welding is more difficult. Also, widespread aluminum and other lightweight material use requires techniques to join dissimilar materials, which adds complexity and cost. In addition, some of the proposed joining technologies are not amenable to high volume production.

Unibody construction is the normal manner of vehicle assembly today. However, these require a large number of individual components that are joined through welding. Spaceframe designs require less joining but are not as economic for high volume production because current techniques are not as automated. They are more labor-intensive (as opposed to equipment intensive) and experience so far indicates they require more rework.

R&D to respond to barriers

Research is being conducted to improve most joining techniques (Table 6). Advanced welding, riveting, and other bonding are all means to join. Advanced welding uses different welding materials and techniques to join aluminum. Riveting can also be used, but with the disadvantage of added joint thickness. Each technology has advantages and drawbacks; research is continuing to improve techniques (Table 6).

Spaceframe research is continuing. Joint research teams from auto and aluminum manufacturers have created new designs that advance the development of the spaceframe. Audi and Alcoa have created the Audi A8 luxury automobile that uses aluminum spaceframe designs. The Chrysler ESX-2 described above is also being designed using a spaceframe BIW. Ford also is preparing for a spaceframe SUV or minivan for sale in the 2001-2002 model years.

Table 6. Advantages and Drawbacks of Aluminum Joining Methods

Joining Method	**Advantages**	**Drawbacks**
Arc Welding	Joint strength Familiar technology	Casting weldability Deformation at heat affected zones
Adhesive Bonding	Joins different materials Sealant	Surface treatment required Demanding assembly practices
Spot Welding	Industry standard process Automated Compatible w/ adhesive bonding	Surface control required Fatigue performance Weld tip life
Riveting, Bolting	Good fatigue performance Dissimilar material joining	Material consumables Added joint thickness
Clinching	Strong as spot welding Fixturing for bonded parts	Low energy absorption Joint loosening

Source: Politos 1995

LWM-sponsored projects – Materials joining

Both projects in the materials joining area are related to adhesive bonds. Developing industry-standard adhesive joint test methods (e.g., to identify peel and/or sheer problems) and facilitating their transfer to the industry are the major goals of one project. It also considers the development of advanced bonding technologies and methods and assessment of the impact of environment and load history on the residual mechanical properties of adhesive joints.

The second project under material joining aims to develop nondestructive evaluation (NDE) and testing techniques that are cost-effective and suitable for real time (e.g., 15-20 seconds per inspection) in a rapid automobile manufacturing environment for on-line inspection of automotive structures with adhesive joints. NDE for adhesive joints is an enabling technology for advanced materials, as it evaluates the quality and strength of bonded and spot-welded joints involving composites and metals as well as dissimilar metals, such as aluminum and steel.

The focus of the last project under aluminum sheet forming has changed recently to the welding area. It addresses improvements in laser and spot welds. Several areas such as surface preparation and uniform weld making are currently being planned for improvements. This project is relatively new and the overall scope is yet to be defined.

LWM-sponsored projects – Energy absorption

There is only a single project studying the crashworthiness of automotive aluminum structures using computational simulations. A finite element base is being developed to assess safety and crashworthiness along with aluminum applicability, required design changes, and weight reduction potential for different automotive aluminum parts. The modeling framework provides an inexpensive and effective tool to facilitate the faster penetration of aluminum in vehicles. The model is currently being validated based on crash tests done by the U.S. Department of Transportation on Audi vehicles. With some necessary customization, the model provides an extremely valuable tool for designers exploring aluminum applications in automobiles.

5.6. Materials Recycling

Cost or technology barriers

While recycling is proving effective for the current mix of aluminum forms within a vehicle, the changing demographics of the types of aluminum in a vehicle could hamper its effectiveness. Tighter controls on alloy composition will be used in the future, both for castings and especially for body structure components. If alloys from recycling are blended then the resulting secondary material may not meet the quality criteria for reuse in the same form. Cost-effective sorting by alloy will improve the value of recycled aluminum.

R&D to respond to barriers

There are two broad areas of research that will improve the recyclability of aluminum. For back-end operations, better sorting technologies can segregate the different types of aluminum. Bulk separation of cast versus wrought will help to identify the higher-value wrought aluminum. Identification and sorting by alloy will help even further by avoiding the quality degradation that comes from mixing alloys.

LWM-sponsored projects – Recyclability

Two projects are currently being funded to look at issues related to aluminum recyclability. The first project is a three-part project, with only one part related to aluminum. It looks at the separation of various wrought aluminum alloys. Two sorting technologies are being proposed for evaluation. The second project examines the hot crush technology for the separation of wrought and cast aluminum (including separation into different alloys) and of aluminum and magnesium. This would enhance the recyclability of aluminum as the use of wrought aluminum in automobiles is increasing by about 7% annually.

6. CONCLUSION

Although aluminum has achieved tremendous growth in the automotive market over the past decade, it has largely been in the specific areas of engine components, transmissions, wheels, and heat exchangers. Further growth is dependent on an increasing penetration into the engine block market and new structural components such as the BIW and closure panels. The cost of engine blocks is hampered by the need for and cost of cylinder liners. The cost of aluminum auto body sheet is still in the $1.30 range or higher, 30% above the $1/lb that is regarded as the price for aluminum to be widely used. This is also higher than the $1.10 to $1.20 that new tailor welded blanking technologies may make economic. Forming and joining technologies are needed for aluminum to be more widely used in the BIW structure, and high-volume designs that utilize aluminum’s strengths would improve penetration. Research involving lower-cost processes or alloys must continue before aluminum can further penetrate these markets. DOE-funded research is important to these areas, and it satisfies the needs of the industry. The currently funded DOE research seems to have the right mix of cast and wrought aluminum projects. Several projects concentrate on the development of databases and predictive models to enhance the application of aluminum in automotive applications. Significant advances have been made in the rapid prototyping of cast aluminum parts and forming of wrought aluminum parts. Further work is needed in the validation of tools developed by means of demonstration in actual automotive parts.

7. REFERENCES

Aluminum Association, Inc. 1997. *The Aluminum Industry Technology Roadmap*. Washington, DC, May. <http://www.oit.doe.gov/aluminum/aluminum_roadmap.shtml>

Aluminum Association, Inc. 1999, *Aluminum Industry Roadmap for the Automotive Market: Enabling Technologies and Challenges for Body Structures and Closures.* Washington DC,, May.

Ashley, Steven 1994, "Aluminum vehicle breaks new ground." *Mechanical Engineering*, Vol. 116, No.2, American Society for Mechanical Engineers, February.

Baron, Jay and Brenda Dickinson 1996, "Tailor Welded Blanks for Automotive Bodies." *OSAT's Focus on the Future*, Office for the Study of Automotive Transportation, University of Michigan Transportation Research Institute, Summer, http://www.osat.umich.edu/newsletters/news10.html

Carpenter, Joe, Sid Diamond, Sara Dillic, Tim Fitzsimmons, JoAnn Milliken and Phillip Sklad 1999, "Overview of DOE's Program on Aluminum and Magnesium for Automotive Applications," *Automotive Alloys 1999*, TMS Publications, Warrendale, PA.

CRU International 1998, *Aluminium Rolling Industry Service Cost Model*. London, England.

Das, Sujit 1999, *The Economic Viability of Aluminum Tailor Welded Blanks*. Report by Oak Ridge National Laboratory to the U.S. Department of Energy. June 1999.

Ducker Research Company 1998, *Report on Aluminum Content in 1999 North American Passenger Cars and Light Trucks*. Ducker Research Company, November.

King, James 1995, "Commercial Aspects of the Alumina and Bauxite Markets: Implications for the Future." *Light Metals: Proceedings of the 124th TMS Annual Meeting*, The Minerals, Metals & Materials Society, pp. 163-169.

Malling, G. F. 1997, *Guide to Suppliers of High-Strength Aluminum Alloys.* K/NSP-524, National Security Program Office, Oak Ridge Y-12 Plant, October.

MIT (Massachusetts Institute of Technology) 1997. *Cost Comparison of Steel and Aluminum Stamped Part.* Material Systems Laboratory.

Plunkert, Patricia A. 1999, *Bauxite and Alumina Mineral Commodities Summary*. U.S. Geological Service, <http://minerals.usgs.gov/minerals/pubs/commodity/bauxite/090399.pdf>

Politos, Dimitrios 1995, *An Economic and Environmental Evaluation of Aluminum Designs for Automotive Structures*. Materials Systems Laboratory, Massachusetts Institute of Technology, May.

Teissier-duCross, Andre R. 1994, "New technology to the rescue for aluminum." *ChemTech*, American Chemical Society, pp. 31-35, June.

Thompson, James V. 1995, "Alumina: Simple chemistry, complex plants." *Engineering and Mining Journal*, Vol. 196, No. 2, February.

U.S. Department of Energy (DOE) 1998, *Office of Advanced Technologies R&D Plan.* DOE/ORO/2065, Office of Transportation Technologies, Energy Efficiency and Renewable Energy, Washington, DC.

Vari-form, 1999, <http://www.vari-form.com/vf.pages/VARb.shtml>

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