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Automotive Lightweighting Materials Benefit Evaluation

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CONTENTS

LIST OF TABLES

EXECUTIVE SUMMARY

This report is the third in a series of studies to evaluate research and development (R&D) projects funded during fiscal years 2000 through 2004 by the Automotive Lightweighting Materials (ALM) effort of the Office of FreedomCAR and Vehicle Technologies (FCVT) of the U.S. Department of Energy (Das et al., 2001 and 2002). The objectives of the evaluations are to assess short-run outputs and long-term outcomes that may be attributable to ALM R&D projects. ALM focuses on the development and validation of advanced technologies that significantly reduce automotive vehicle body and chassis weight without compromising other attributes such as safety, performance, recyclability, and cost. Funded projects range from applied materials science research to applied research in production environments. Collaborators on these projects include national laboratories, universities, private-sector firms such as leading automobile manufacturers and their suppliers, and nonprofit technology organizations.

The specific goals of ALM are to develop by 2010 material and manufacturing technologies that, if implemented in high-volume production vehicles,[1] could cost-effectively reduce the weight of light-duty vehicles by 50 percent (relative to 2002 comparable vehicles) (Carpenter et al., 2006a, 2006b; U.S. DOE, 2005a). ALM is currently pursuing five areas of research with regard to different lightweighting materials areas: cost reduction, manufacturability, design data and test methodologies, joining, and recycling and repair (U.S. DOE, 2005a). Priority is given to activities aimed at reducing costs through development of new materials, forming technologies, and manufacturing processes. Priority lightweighting materials include advanced high-strength steels, aluminum, magnesium, titanium, and composites including glass and carbon-fiber (U.S. DOE, 2005a).

ALM activities support the lightweighting goals of the predecessor program Partnership for a New Generation of Vehicles (PNGV), as well as the ongoing Freedom CAR programs. The FreedomCAR partnership's lightweighting goal is 50% weight reduction for the average light-duty vehicle. This goal is more aggressive than the PNGV's goal which was a 40% weight reduction. Thus, ALM activities emphasize magnesium and carbon-fiber-reinforced polymer-matrix composites for long-term gains, while continuing work on aluminum and advanced high-strength steels for the mid term. Advanced high-strength steel is being considered by ALM because it has a 25% weight-reduction potential, much higher than the potential of conventional steel. The FreedomCAR Partnership also conducts research on technologies to meet short-term energy efficiency goals and to provide environmental benefits. It also has a focus on long-term mass production of hydrogen powered fuel-cell vehicles.

There are two foci of this evaluation: The first focus area was carbon-fiber-reinforced polymer-matrix composites. The assessment of this focus area was conducted during the summer of 2005 and addressed 5 of the 23 ALM polymer composites R&D projects. The second part of the assessment, conducted during late 2005 and early 2006, assessed 4 projects focused on materials other than polymer composites. These projects and their goals are detailed in Table E.S.1.

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[1] High-volume production is considered to be between 50,000 to 100,000 units per year or greater.

Table E.S.1: Projects and Their Objectives	
Project	**Objectives**
Carbon-fiber-reinforced polymer-matrix composites projects	
Composite-intensive body structure for focal project 3 [1]	Design, analyze, and build a composite-intensive body-in-white, while meeting structural and production objectives such as high-volume production techniques yielding 60 percent mass reduction at cost and structural performance parities with steel.
Durability of carbon-fiber composites	Develop experimentally-based, durability-driven design guidelines to ensure the long-term (15-year) integrity of representative carbon-fiber-based composite systems in large structural automotive components.
Low-cost carbon fibers from renewable resources	Develop carbon fibers from high-volume, low-cost, renewable or recycled fiber sources to reduce precursor and processing costs for the large-scale automotive applications.
Low-cost carbon-fiber development program	Develop technologies needed to produce carbon fiber for automotive applications at a cost of \$3.00 to \$5.00 per pound in quantities greater than one million pounds per year, with tensile strength greater than 400 ksi, modulus greater than 25 Msi, and strain at failure greater than 1 percent.
Modeling of composite materials for energy absorption	Develop analytical and numerical tools to predict the behavior of carbon-fiber-based components in vehicular crash.
Non-composites projects	
Active flexible binder control system for robust stamping	Develop flexible binder control technology, in conjunction with innovative tool designs and closed-loop control to produce robust processing, for stamping materials. This allows the use of computer simulation and process optimization to predict optimum binder force trajectories that can be entered into programmable hydraulic cushions to control binder actions in mechanical and hydraulic presses. This project focuses on aluminum and advanced high-strength steel.
Lightweighting front structures	Benchmark, develop, and document proven solutions that will balance the interaction of material, manufacturing, and performance of lightweighting automotive steel front structures. The initial focus has been on automotive front-end systems solutions utilizing advanced high-strength steel designs.
Magnesium powertrain cast components	Demonstrate and enhance the feasibility and benefits of using magnesium alloys in place of aluminum in structural powertrain components, achieving at least a 15-percent weight reduction for cast components.
Structural cast magnesium development	Develop and demonstrate the technical feasibility of processes for casting large automotive parts from magnesium.

[1] This project is a part of the validation activity (called focal projects) demonstrating one of ALM's goals of reducing the lead time to bring new technology into the marketplace.

These projects were selected because they are illustrative of major lightweighting materials research areas undertaken by ALM. The projects involve different lightweighting materials and examine issues important for any lightweighting material: durability, cost, performance, and safety. The R&D projects reflect multiple partners involved in the effort. In choosing the projects, we took into consideration the level of funding and project status (e.g., projects completed and those on-going).

Due to the significant focus on cost reduction as a means to improve the viability of carbon-fiber polymer-matrix composites, two projects dealing with costs were selected: *low-cost carbon fibers from renewable resources* and *low-cost carbon-fiber development program*.[2] Similarly, two projects, *durability of carbon-fiber composites* and *modeling of composite materials for energy absorption*, fall under the category of enabling technologies, focusing on durability and safety areas, respectively. The two magnesium projects included consider using magnesium in different automotive components: powertrains and structural supports.

Four projects have larger budgets than other ALM R&D projects. The *composite-intensive body structure for focal project 3*, *magnesium powertrain cast components*, and *structural cast magnesium development* projects are 100 percent cost-shared by the auto industry and cover technology development. One of the enabling technologies projects—*durability of lightweighting composite structures* project—is the ALM project with the largest budget to date and is being carried out in close coordination with the Automotive Composites Consortium (ACC).

These nine projects reflect differences in project partners. For example, only national laboratories were involved in the *modeling of composite materials for energy absorption*, while private sector and national laboratory collaboration occurred in the *low-cost carbon-fiber development program*. The *structural cast magnesium development* project had 34 participating partners, including three national laboratories (Lawrence Livermore, Oak Ridge, and Sandia). Two projects, i.e. *durability of carbon-fiber composites* and *low-cost carbon-fiber developmen*t, were complete at the time of their evaluations. Other projects are on-going, although several have projected completion dates in 2006.

We chose an evaluation framework that would meet our goal of evaluating both short-run outputs and long-run outcomes of the R&D projects. This framework addresses important aspects of the benefits of R&D projects, using both qualitative and quantitative measures. We used four methods to evaluate the short-run outputs and long-term outcomes of ALM projects:

- *Qualitative assessment.* We collected and assessed participant views about the benefits of the projects. Questions addressed whether the projects met their technical objectives, yielded knowledge, would have been conducted without federal support, enhanced collaboration among the participants, and produced results sufficient to make the lightweighting material a viable option for the auto industry. In the second set of evaluations, we added a question on whether the results would be incorporated into product design for light-duty vehicles, keeping in mind that several projects were on-going at the data collection time. Answers to these questions indicated, in most instances, the immediate outputs of the R&D projects.

[2] For easier reading, project names are italicized in the text of this paper.

- *Indicators recommended by National Academy of Sciences' Committee on Science, Engineering, and Public Policy (COSEPUP)*. Participants' answers to prepared questions and a review of the projects' materials enumerated the number of publications and presentations associated with the projects, established whether the projects benefited from outside peer review, and whether the projects enhanced U.S. international competitiveness. These answers indicated both near (e.g., number of publications produced by the end of a project) and long-term benefits (knowledge level gained through the publications and increased international competitiveness of the Big Three automakers).

- *Quantitative benefits.* Researchers were asked to provide the number of undergraduate and graduate students supported each year on the project[3], whether patents and copyrights were applied for and received, whether software packages or project deliverables were developed and commercialized. If there were software packages, we asked if they had been distributed to the Big Three automakers, what was the reception, and equally important, whether the deliverable would be used in the decision-making process of the original equipment manufacturers (OEMs) in incorporating lightweighting materials in production. These are both short-run outputs and long-term outcomes.

- *Economic analyses.* We conducted a benefit-cost analysis to monetize values for the benefits and costs of each project. While the benefits are due mainly to the commercialization of new technologies, companies also received benefits accruing from federal support. We developed forecasts to the year 2030 of market penetration of new vehicles benefiting from the new technologies. The benefits are estimated using a Delphi technique and are based on the projected market penetration of lightweighting materials in light-duty vehicles. Benefits examined include energy savings, reductions in air pollutants [e.g., carbon dioxide (CO_2), nitrogen oxides (NOx)], and security benefits. We assigned values to each benefit, and estimated benefits and costs. We defined costs as DOE support and private sector cost sharing. We calculated net present values for the benefits and the ratio of benefits to costs for each project. In addition, we calculated monetized cost savings to industry by having access to federal R&D resources. In general, this is a long-term outcome because of the on-going nature of some of the projects and the time frame between completion of a project and introduction into the marketplace. The short-term outrcomes are the cost savings accrued to industry by having access to federal R&D resources or DOE involvement in a material area.

These broad methods were initially tested in two previous reports where the primary interest was on framework development. They were tested on a limited number of projects ALM funded in the mid to late 1990s (see Das et al., 2001 and 2002).[4] Where necessary we expanded the methodology to better assess attributes of the R&D projects, specifically including a Delphi technique for the benefit-cost analysis. Moreover, these methods complement the benefits matrix developed for DOE's reports to Congress mandated under the Government Performance and

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[3] The second phase also sought information about participation by undergraduate students.

[4] The methods were subjected to numerous internal and external DOE peer reviews. In addition, two peer-reviewed publications resulted, where the appropriateness of the methods were scrutinized (Das et al., 2004; Peretz et al., 2005).

Results Act of 1993 (GPRA). At this point, economic, environmental, and security benefits and costs are reported to Congress. Our framework also includes realized knowledge benefits and costs, yet to be reported to Congress, through the qualitative assessment (knowledge gains); through the COSEPUP's coverage of publications and presentations; and through the quantitative assessment of patents, copyrights, software or other project deliverables, and graduate student support. All these are indicators of knowledge benefits.

When interpreting the results, the reader should keep in mind that respondents were speaking for their individual projects, rather than a collective review of carbon-fiber polymer composites or magnesium, for example. In addition, there may be a difference between technical feasibility, which was addressed implicitly in each of these projects, versus a business decision by the OEMs to incorporate lightweighting materials. The results from each lightweighting material covered in this evaluation are promising, but they indicate that there remains work to be done before significant transitions in material use occur.

Table E.S.2 presents the results of the qualitative assessment for the composite projects, along with results from the other lightweighting materials projects. Overall, the results for the carbon-fiber composites projects are positive. All the respondents on two of the projects and most participants on the other three carbon-fiber composites projects agreed that the project met its technical objectives. Participants in two projects (c*omposite-intensive body structure for focal project 3* and *low-cost carbon fibers from renewable resources*) qualified their negative responses by pointing out that the *composite-intensive body structure project* was on-going and, hence, it was premature to say that the objectives were met. Other respondents were involved in only one task and did not wish to speak for the overall project. Similar qualifiers were offered by some participants in the *low-cost carbon fibers from renewable resources* project, but 17 percent of this project's respondents indicated that objectives were not met because technical challenges were revealed that need to be addressed.

There was a near unanimous, positive response that the carbon-fiber composites projects produced knowledge, and a clear indication that these composites research projects would not be undertaken without DOE support. (The DOE funding question was not posed to the DOE laboratory researchers involved in the *modeling of composite materials for energy absorption* project.) Reasons for not pursuing research without DOE involvement included risk, cost, resource or knowledge-base required, and uncertainty regarding commercialization. In general, each project enhanced collaboration. Respondents who believed future collaboration was uncertain had concerns related to proprietary business information and finding the correct mix of technical skills.

Finally, there was less agreement on whether the results of the project were sufficient for carbon fibers to be a viable option for the automobile sector. Interestingly, the participants involved in the two projects focused on cost were more inclined than the participants in the other projects to believe that their project had produced results sufficient for carbon-fiber polymer composites to be a viable material option. When asked about barriers to wide-scale introduction of carbon fibers, respondents across the board cited cost and manufacturing/performance issues.

Table E.S.2: Summary of Qualitative Assessments						
Project	**Met technical objectives?**	**Yielded knowledge?**	**Participated without DOE funding?**[1]	**Was collaboration enhanced?**[2]	**Will results be incorporated into product design for light-duty vehicles?**[3]	**Results sufficient for material to be a viable option?**
Carbon-fiber Composites						
Composite-intensive body structure for focal project 3	Yes (50%, N=3) [4]	Yes (100%, N=6)	Yes (16%, N=1)	Yes (100%, N=6)	na[5]	Yes (33%, N=2)
Durability of carbon-fiber composites	Yes (88%, N=7)	Yes (88%, N=7)	Yes (33%, N=1)	Yes (86%, N=6)	na	Yes (14%, N=1)
Low-cost carbon fibers from renewable resources	Yes (67%, N=4)	Yes (100%, N=6)	Yes (0%, N=0)	Yes (50%, N=3)	na	Yes (83%, N=5)
Low-cost carbon-fiber development program	Yes (100%, N=6)	Yes (100%, N=6)	Yes (0%, N=0)	Yes (100%, N=6)	na	Yes (67%, N=4)
Modeling of composite materials for energy absorption	Yes (100%, N=2)	Yes (100%, N=2)	N/A[1]	Yes (100%, N=2)	na	Yes (50%, N=1)
Non-Composite Lightweighting Materials Projects						
Active flexible binder control system for robust stamping	Yes (83%, N=5)	Yes (100%, N=6)	Yes (17%, N=1)	Yes (83%, N=5)	Yes (40%, N=2)	Yes (67%, N=4)
Lightweighting front structures	Yes (100%, N=3)	Yes (100%, N=3)	Yes (33%, N=1)	Yes (100%, N=3)	Yes (50%, N=1)	Yes (67%, N=2)
Magnesium powertrain cast components	Yes (55%, N=16)	Yes (90%, N=26)	Yes (32%, N=9)	Yes (93%, N=26)	Yes (32%, N=8)	Yes (55%, N=16)
Structural cast magnesium development	Yes (90%, N=18)	Yes (100%, N=20)	Yes (19%, N=3)	Yes (100%, N=20)	Yes (60%, N=9)	Yes (58%, N=11)

(1) This question was not posed to the national laboratory researchers participating in this research.
(2) Measured as response to whether participants are willing to collaborate in the future. This is a more precise measurement than in our previous studies where we simply asked the interviewees if collaboration were enhanced.
(3) This question was not applicable to the university and national laboratories participating in this research.
(4) (N) = the number of respondents who answered the question as noted, not the total number of respondents.
(5) This question was not posed during the phase of research that addressed carbon-fiber composite projects.

Table E.S.2 also displays the qualitative assessments for the magnesium, advanced high-strength steel, and aluminum projects and includes participants' assessment of whether the results would be incorporated into product design for light-duty vehicles. This question was targeted primarily to the Big Three automakers and their suppliers. It was not posed to national laboratories and not applicable to universities and technical societies that might be engaged in the research effort.

Nearly all respondents in three of the four non-composites projects believed his or her respective project had met its technical objectives. Perspectives on the fourth project, *magnesium powertrain cast components*, were mixed. However, many of the investigators who replied "not sure" or "no" explained that they did so because the project was still on-going or that they were involved in only one task and could not speak for the entire project.

Almost all investigators believed that their project yielded knowledge. One-third or fewer investigators believed that their respective projects would have occurred in the absence of DOE participation and/or funding, attesting to the crucial role of DOE. Several of these investigators noted that they would have had lower amounts of funding. Respondents noted that DOE's participation fosters collaboration, attracts major participants, and is necessary because costs are too great for any single firm to bear.

In two of the four projects—*lightweighting front structures* and *structural cast magnesium development*—participants agreed unanimously that collaboration was enhanced; while in the remaining projects, solid majorities of participants—83% and 93%—believed collaboration to have been enhanced.

Although the Big Three must cost share in some of the projects, an important assessment is whether the results of these projects will be incorporated into product design for vehicles. The results are mixed in each case. However, the most positive result, with 60% of participants believing the results will be incorporated into product design, occurs in the *structural cast magnesium development* project. This response, although favorable, is surprisingly low given that the 2006 model year Corvette Z'06 already uses a magnesium engine cradle that emanated from the project. The least favorable response occurred in the magnesium powertrain cast component project, perhaps reflecting the on-going nature of the research and the risk associated with a magnesium engine.

There were comparable reactions to the question on whether the results of an individual project were sufficient for the material to be a viable option. There was not an overwhelming endorsement of any of the projects—affirmative responses range from 55 to 67 percent. Responses could be an acknowledgement of the on-going nature of the project or barriers that remain.

It may be unrealistic, considering the remaining research to be done on any of the lightweighting materials, to assume that any one of the numerous R&D efforts undertaken would be the turning factor for wide-scale adoption by the automobile industry. In Table E.S.3 we summarized responses to an open-ended question on barriers to wide-scale introduction of carbon-fiber polymer composites, aluminum, advanced high-strength steel (AHSS), and magnesium in the

Table E.S.3: Barriers to Wide-Scale Introduction

Barrier Cited	Research Project								
	Composite-intensive body structure development for focal project 3	Durability of carbon-fiber composites	Low-cost carbon fibers from renewable resources	Low-cost carbon-fiber developme nt project	Modeling of composite materials for energy absorption	Active flexible binder control system for robust stamping	Light-weighting front structures	Magnesium powertrain cast components	Structural cast magnesium development
Cost	✓	✓	✓	✓	✓	✓		✓	✓
Manufacturing/performance issues	✓	✓		✓	✓	✓	✓	✓	
Corporate culture/resistance to change	✓			✓	✓	✓		✓	
Sufficient availability of lightweighting material		✓	✓						
Adequate material science assessment of low cost carbon fiber			✓						
Market demand for lightweighting autos				✓					
Gasoline prices still relatively low				✓		✓			
Downstream conversion processes to deal with low cost carbon forms				✓					
Material uniformity				✓					
Infrastructure demands							✓	✓	✓
Quality, safety standards							✓	✓	
Corrosion								✓	✓
International tariff policies								✓	✓
Competing technologies, materials								✓	✓
Engineering community acceptance									✓
Other									✓

manufacture of light-duty vehicles within the U.S. automotive industry. A mark in the column indicates that that barrier was noted by at least one participant in the given project.

Cost of the material was identified as a barrier to wide-scale introduction in eight of nine projects. In only one instance, the *lightweighting front structures* project which used advanced high-strength steel, was cost not mentioned. Other prominent barriers were manufacturing/performance issues and the corporate culture of the Big Three automakers (e.g., a resistance to change).

Table E.S.4 presents the results from program evaluation measures recommended by the National Academy of Sciences (NAS). The number of publications and presentations varied considerably, but it appears dependent primarily on the number of participants per research project. It is noteworthy that projects with heavy involvement from the private sector can publish extensively. This finding is somewhat different from our previous evaluations. In at least one situation—*low-cost carbon-fiber development* program—publishing the results was a corporate expectation. Publications are often used as an employee evaluation metric at national laboratories, so large number of publications would be expected from projects involving the laboratories, such as the *durability of carbon-fiber composites* project and the *modeling of composite materials for energy absorption* project, despite the smaller number of researchers on the R&D effort.

As we found in our previous analyses, none of the projects had outside review panels as envisioned by the National Academy of Sciences, although each project included outside review albeit by members of the ACC, DOE, USAMP, Auto/Steel Partnership, or experts within a firm but not an active participant in the R&D effort. For several years, an independent outside panel convened by the National Academy of Sciences' National Research Council reviewed FreedomCAR's predecessor, Partnership for a New Generation of Vehicles (PNGV) (NRC, 2001b).[5] In the fall of 2004, the Board on Energy and Environmental Systems assembled a team to review FreedomCAR and issued its first report in 2005 (NRC, 2005).

Responses suggest that the U.S. is neither leading in research in these areas nor leading in commercialization of these technologies. The exception is the carbon-fiber polymer composites area, where half of respondents in four of the five projects believed the U.S. was leading in research. However, there was relatively strong agreement that the international competitiveness of the U.S. is improved by these research programs.

Table E.S.5 presents the quantitative benefits of all nine projects. Graduate students were involved in each project, including those that did not have a university as an active university participant (*low-cost carbon-fiber development program* and *modeling of composite materials for energy absorption*, *active flexible binder control system for robust stamping, lightweighting front structures*). Undergraduate students worked on both magnesium-focused projects.[6]

[5] Seven reviews were conducted on PNGV by NRC's Board on Energy and Environmental Systems.
[6] As previously noted, we did not seek information about undergraduate student involvement in the carbon fiber polymer composites projects.

Table E.S.4: Committee on Science, Engineering, and Public Policy Indicators						
Project	**Number of publications produced, including technical reports**	**Number of presentations excluding conference proceedings**	**Did it use an outside review panel?(1)**	**The United States is leading in research in this field(2)**	**The United States is leading in commercialization in this field(2)**	**The project will improve U.S. international competitiveness(3)**
Composites						
Composite-intensive body structure development for focal project 3	21	--	No	50% (N=3)	0% (N=0)	67%
Durability of carbon-fiber composites	40(4)	--	No	50% (N=3)	17% (N=1)	100%
Low-cost carbon fibers from renewable resources	11	8	No	0% (N=0)	0% (N=0)	100%
Low-cost carbon-fiber development program	9	15	No	50% (N=3)	17% (N=1)	50%
Modeling of composite materials for energy absorption	25	--	No	50% (N=1)	0% (N=0)	100%
Non-Composite Lightweighting Materials Projects						
Active flexible binder control system for robust stamping	33	3	No	33% (N=2)	17% (N=1)	100%
Lightweighting front structures	4	5	No	0% (N=0)	0% (N=0)	67%
Magnesium powertrain cast components	26	33	No	10% (N=3)	11% (N=3)	86%
Structural cast magnesium development	119	22	No	5% (N=1)	11% (N=2)	74%

(1) This question applies to a peer review process as envisioned by the NAS Committee on Science, Engineering, and Public Policy.
(2) Percentage of respondents who selected “leading” in response to the question, “The United States is leading, following, or about even to other countries with respect to ….”
(3) Percentage of those responding “strongly agree” or “agree” with statement: “this project will help the U.S. automotive sector to be more competitive in the international market for light-duty vehicles than would have occurred without involvement in the R&D project.” It should be noted that similar results were found to the responses to this statement: “this project will help the U.S. automotive sector to be more competitive in the domestic market for light-duty vehicles than would have occurred without involvement in the R&D project.”
(4) This includes one dissertation.

Table E.S.5: Quantifiable Benefits					
Project	**Student involve-ment (year of project/ # of students)**	**Degrees sought by students**	**Patents Applied for/ Received**	**Copyrights Applied for/ Received**	**Software Developed and Commercialized**
Composites					
Composite-intensive body structure development for focal project 3	1/3 2/1 3/2 4/2 5/1	Master's, Ph.D, or Post-doctoral	No	No	No
Durability of carbon-fiber composites	1/1 2/2 3/2 4/2 5/2	Master's and Ph.D.	No	No	No
Low-cost carbon fiber from renewable resources	3/1 4/1 5/1	Ph.D.	Yes(2)	No	No
Low-cost carbon-fiber development program	1/3 2/4 3/5 4/3 5/2	Master's and Ph.D.	No	Internal to firm	No
Modeling of composite materials for energy absorption	1/4 2/4 3/4 4/4 5/3	Master's and Ph.D.	No	No	Yes
Non-Composite Lightweighting Materials Projects					
Active flexible binder control system for robust stamping	1/4 2/4 3/6	Master's and Ph.D.	No(3)	No	See text summary
Lightweighting front structures	1/3	Master's	No	No	Yes(4)
Magnesium powertrain cast components	1/0 2/0 3/1 4/6 5/15 6/11	Bachelor's, Master's, and Ph.D.	Yes(5)	No(6)	See text summary
Structural cast magnesium development	1/7 2/11 3/18 4/21 5/30	Bachelor's, Master's, and Ph.D.	No(7)	No	See text summary

(1) One researcher is anticipating developing and commercializing software in the future.
(2) Another application for a patent has been filed.
(3) One respondent anticipates his firm applying for two patents sometime in 2006.
(4) Developed, but not commercialized.
(5) One respondent anticipates his firm applying for a patent in 2007; another anticipates applying for two patents in 2006; and a final anticipates applying for a patent although the year is not certain.
(6) One respondent anticipates his firm applying for two copyrights sometime in 2006.
(7) One representative anticipates his firm applying for a patent sometime in 2006.

Other metrics concern patents, copyrights, and commercialization of software packages. Among the carbon-fiber polymer composites projects, one has sought/received a patent, and one has received a copyright (internal to the firm). One project—the *modeling of composite materials for energy absorption* project—has developed software, and another anticipates doing so in the future. Similarly, among the non-composites projects, one patent has been sought, and respondents expect a number of patents and copyrights stemming from this research to be sought in 2006 or 2007.

As evidenced here, not every research project will result in deliverables or products that will be commercialized. But for those that do, it is important to ascertain the reception of these items by the auto industry and equally important to determine whether the automakers and/or their suppliers will make use of the deliverables in their decision-making processes for lightweighting vehicles. Therefore, of interest in the overall evaluation effort is the reaction of the Big Three automakers to the software package or other deliverables finalized from the project.

The objective of the *modeling of composite materials for energy absorption* project was to develop analytical and numerical tools, including software. The researchers modified existing tools for this effort. Participants' estimations of modifications needed to make the tools applicable to this R&D effort ranged from 21% to 50%. Part of the software packages developed as a result of the R&D project was commercialized and introduced into the marketplace between 2001 and 2004. The participants in the *modeling of composite materials for energy absorption* reported that the reception from the automobile industry was positive and the results are being used in composite crash analysis and design.

The output of the *durability of carbon-fibers composites* project was durability-based guidelines. The results were presented to the Big Three automakers at various times throughout the project period. All researchers who responded felt that the guidelines had been well-received by the Big Three and provided them with valuable information. In addition, 88 percent of the respondents felt that the information will be used by the Big Three.

There were four deliverables from the *active flexible binder control system for robust stamping* project: design guidelines for flexible binders, 26-cylinder binder load control unit, computer simulation/optimization codes, and control algorithm for non-linear systems. Respondents did not expect commercialization of the design guidelines or the binder load control unit, and reception by the industry of these deliverables was largely unfavorable.

It appears that the following products from the *magnesium powertrain cast components* project have potential for commercialization: alloy testing, selection, and database; coolant-corrosion investigation/evaluation; some components of the current and future research for North America; component filling and solidification models; component tooling; excised specimen testing; and engine durability testing. Considering that the project is on-going, it is not surprising that anticipated dates of commercialization range from 2006 to 2008 at the earliest. The reaction of the Big Three to the deliverables has been favorable or very favorable in most cases. In addition, respondents believe that each of these products would be used by the OEMs in their decision-making process for incorporating magnesium into automotive production.

From the *structural cast magnesium development* R&D effort, there is potential for commercialization for the magnesium alloy database; radioscopic standard for magnesium castings; and failure model. Dates range from 2006 to 2010. All the products were favorably or very favorably received. Moreover, the respondents indicated that the products would be used by the Big Three in decision making beyond General Motors' Corvette Z'06.

It should *not* be an expectation that patents, copyrights, or software originate from every R&D project funded by ALM. That patents and copyrights were applied for and received, and software tools were commercialized in three of the five composites projects is a significant intellectual contribution. That commercialization will not occur for many products of the *active flexible binder control system* or only a portion of the products from the *structural cast magnesium project* should not be perceived as a reflection of the inadequacy of the project's efforts to incorporate aluminum or magnesium into automobiles. Disagreement about commercialization in the *magnesium powertrain cast components* may reflect that there are numerous products from this research effort, the effort is on-going, and commercialization should in fact not be an expectation for everything resulting from the project.

The results of the economic analyses—benefit-cost ratio and person-year and cost savings from having access to federal R&D funds—are given in Table E.S.6, E.S.7, and E.S.8. The benefit-cost analysis takes into account energy, environmental, and security benefits. The project costs include both federal funding and private-sector matching funds.[7]

In every case, the benefit-cost ratios indicate significant benefits for these projects. It must be noted, however, that several uncertainties are associated with these numbers, as is typical for benefit-cost analyses. First, the commercialization date and market penetration rates for each technology are uncertain. The analysis assumes dates for initial commercialization and market penetration rates that may or may not come true. Second, the projects reflect uncertainty in the level of benefits associated with each new vehicle that contains new lightweighting materials. Third, uncertainties exist concerning the monetary values to be assigned to each benefit, e.g. values of reducing CO_2, oil imports, etc. Fourth, investment costs to be borne by the automobile manufacturers and their suppliers to implement the new technologies are not fully captured in this analysis. The base, moderate, and high cases represent low, medium, and high monetary values for energy, environmental, and security savings.

Revisions were made to the evaluation methodology used to determine person-year and cost savings in Phase Two (aluminum, magnesium, and advanced high-strength steel projects). We kept the inquiry on whether the company or institution would have participated without federal

[7] Note that we estimated benefits based on the projected market penetration of materials and technologies using a Delphi technique.

Table E.S.6: Benefit-cost Ratios				
Project	**Project Cost ($ millions)**	**B-C Ratio Base Case***	**B-C Ratio Moderate Case***	**B-C Ratio* High Case**
Composites				
DOE (carbon-fiber composites)	66.4	41 (35)	78 (60)	147 (104)
Composite-intensive body structure development for focal project 3	5.1	126 (108)	236 (183)	447 (318)
Durability of carbon-fiber composites	7.2	61 (52)	120 (93)	235 (168)
Low-cost carbon fiber from renewable resources	3.1	124 (106)	245 (190)	479 (341)
Low-cost carbon-fiber development program	3.6	188 (161)	341 (265)	631 (449)
Modeling of composite materials for energy absorption	4.4	73 (62)	150 (117)	301 (215)
Non-Composite Lightweighting Materials Projects				
DOE (Aluminum)	32.9	425 (324)	669 (508)	1034 (794)
Active flexible binder control system for robust stamping	1.5	3217 (2360)	5207 (3950)	8540 (6563)
DOE (Magnesium)	14.6	106 (90)	259 (199)	606 (417)
Magnesium powertrain cast components	4.3	156 (131)	424 (327)	1023 (696)
Structural cast magnesium development	8.2	34 (29)	86 (67)	198 (134)
DOE (High-strength steel)	10.5	472 (407)	818 (644)	1476 (1056)
Lightweighting Front Structures	3.1	804 (694)	1443 (1136)	2672 (1908)
*Numbers inside parenthesis indicate benefit-cost ratios without taking into account environmental and security benefits.				

Table E.S.7: Person-Year and Cost Savings				
	Composite-intensive body structure development for focal project 3	**Durability of carbon-fiber composites**	**Low-cost carbon fibers from renewable resources**	**Low-cost carbon-fiber development program**
Benefits Received from Participating in R&D Effort				
Person-years to achieve same technical knowledge	For university involvement in specific task: less than 1 year For other private-sector firms: (a) 3 to 5 years; (b) more than 5 years	Respondent 1: 1 to 2 years Respondent 2: more than 5 years	Less than 1 year	More than 5 years
Cost savings		Respondent 1: More than $200,000		More than $200,000
Productivity or efficiency gains		Respondent 1: Yes Respondent 2: Not sure		No[1]
Percentage of productivity or efficiency gain		1 to 15 percent		1 to 15 percent
Costs to Achieve Same Technical Knowledge				
Level of R&D effort without financial support from DOE			1 person in year 1, at average person-year cost of $175,000, 25 percent effort; 2 persons each in years 2 and 3, at average person-year cost of $175,000, 50 percent effort	Between 1 and 3 persons per year for a 4-year period at ranges of effort <10% to around 60%
Person-years to achieve same technical knowledge			1.25 years	Between 5 and 6
Total cost to achieve same technical knowledge			$220,000	$2-3 million

[1] One respondent commented that there was an efficiency gain in terms of R&D knowledge and personnel experience.

support, and if the response was no, we sought factors that would affect the decision.[8] We also followed up with the investigators by asking them to complete a table on person-years committed by organization, project costs committed by organization, and year of introduction of product, with and without federal support. We then asked them to calculate the benefits from participating in R&D (difference between with and without federal support). To ensure confidentiality and because there were multiple firms involved in this effort, the person-years and total costs savings are presented in aggregate form.[9] The results are presented in Table E.S.8.

Table E.S.8: Person-Year and Cost Savings and Market Entry Impacts

Project	Person-years saved	Cost savings ($)	Market entry expedited by X years
Active flexible binder control system for robust stamping project	10	5,695,000	4-5
Lightweighting front structure project	7	2,200,000	6
Magnesium powertrain cast components project[(1)]	52.5	27,230,000	48
Structural cast magnesium development project	21+[(2)]	12,000,000+	3-10

(1) There were several key managers from the auto industry involved in this project. To avoid "double counting," we added the numbers provided by one representative of each auto company.
(2) "+" is used because one respondent indicated the person-year and cost savings were innumerable.

Our framework specifically focuses on multiple techniques for evaluating the short-run outputs and long-term outcomes of the nine R&D projects. When the results are viewed collectively, there are innumerable benefits associated with these efforts.

As noted at the beginning, there are two perspectives that can be taken from this evaluation. When considering an overwhelming majority of the indicators selected, the responses are outstanding. There remain questions about whether the results will be incorporated or whether a material is a viable option. What this evaluation has highlighted are the ongoing challenges to

8 The term "counter-factual" is used to assess benefits to projects that *would have* proceeded in the absence of federal funding. As noted in our response sets, many of the companies would *not* have pursued this research without DOE participation, including funding, availability of researchers at national laboratories, etc. We present the person and cost savings as reported by the key managers, even if their company would have pursued the R&D without federal support.

9 This is consistent with Link's methodology (1997). Responses are measured as the *difference* between "person-years committed by your organization" and "person-years needed by your organization to achieve same technical knowledge" and "project costs committed by your organization" and "total costs needed by your organization to achieve same technical knowledge."

change in the automobile industry: there may remain a gap between establishing the technical feasibility of a material or process and making a business decisions to move forward with a lightweighting material.

Moving to lightweighting materials must overcome at least two serious “catch-22s.” First, it must be understood that OEMs are not material producers but parts consumers. OEMs may not demand lightweighting parts until they can be proven to be cost-competitive, reliable, and amenable to mass manufacture. On the other hand, suppliers may not invest in the R&D for lightweighting parts until the OEM's begin to demand parts made from lightweighting materials. A second “catch-22” involves lack of expertise in lightweighting materials in both OEM and supplier organizations. Again, neither may have incentive to develop such expertise until it can be shown that such expertise is needed. But, the expertise itself is needed to understand the potentials and limitations of the new materials. These catch-22s make it difficult for the industry as a whole to move to new materials as quickly as would be necessary to achieve energy, environmental, and security benefits for the overall public interest.

The ALM effort helps to reduce the risks to the OEMs and suppliers from exploring new materials. The program also facilitates discussion and collaborations among the OEMs and suppliers to help overcome the catch-22s described above. The program is valuable in helping to identify next steps to developing new lightweighting parts. The ALM effort brings materials expertise found in national laboratories and universities that can get the discussions and R&D moving. It has also been shown that the projects help to build a critical mass of professional expertise needed to move the industry forward in these materials areas. This expertise could then direct future R&D in many new directions, not only in the directions represented by the ALM-funded projects.

1. INTRODUCTION

This report is the third in a series of studies to evaluate research and development (R&D) projects funded by the Automotive Lightweighting Materials (ALM) effort of the Office of FreedomCAR and Vehicle Technologies (FCVT) of the U.S. Department of Energy. FCVT is housed in DOE's Office of Energy Efficiency and Renewable Energy (EERE).[10] The first and second reports in this series focused on developing the framework for the benefit-estimation methodology, using a few aluminum and polymer composite projects supported by ALM between fiscal year (FY)1995 and FY1999 to illustrate the methodology (see Das et al., 2001 and 2002). The objective of the program evaluation is to identify short-run outputs and long-run outcomes that may be attributable to the ALM R&D projects.[11]

ALM seeks to make vehicles more efficient by making them lighter (Carpernter, Jr., et al., 2006a). ALM is a collaborative effort involving DOE, the automotive industry, materials suppliers, national laboratories, academia, and nonprofit technology organizations (U.S. DOE, 2005a). The ALM effort brings participants together to work through such organizations as the FreedomCAR Materials Technical Team, the Automotive Composites Consortium (ACC), and the United States Automotive Materials Partnership (USAMP) and share technological and environmental concerns (U.S. DOE, 2005a).

The specific goal of ALM is to develop by 2010 material and manufacturing technologies that, if implemented in high volume, could cost-effectively reduce the weight of automotive vehicles by 50 percent (relative to 2002 comparable vehicles) (U.S. DOE, 2005a). ALM focuses on the development and validation of advanced technologies that can provide vehicle body and chassis weight reductions without compromising other attributes such as safety, performance, recyclability, and cost (U.S. DOE, 2005a). Funded projects range from applied materials science research to applied research in production environments. Collaborators on these projects include national laboratories, universities, private-sector firms, such as leading automobile manufacturers and their suppliers, and nonprofit technology organizations (U.S. DOE, 2005a).

ALM is currently pursuing five areas of research with regard to lightweighting materials: cost reduction, manufacturability, design data and test methodologies, joining, and recycling and

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[10] For an organization chart, see <www1.eere.energy.gov/office_eere/pdfs/eere_orgchart.pdf>, accessed 2/17/06.

[11] We use the term benefits when considering outputs and/or outcomes of the research evaluated in this report. The program evaluation literature generally defines outputs as immediate results of a project, e.g., project objectives met, publications generated, or graduate students involved in the R&D effort. Outputs can be qualitative, e.g. were objectives met, or quantitative, e.g. number of graduate students supported. Outcomes are longer term impacts, such as the penetrations of lightweighting vehicles in the market and a reduction in emissions or dependency on foreign oil occurred. Outcomes are generally thought of as being quantitative, although long-term knowledge can be an outcome. One could argue, of course, that a longer term outcome could result from a short-run output with the number of citations to a publication, traditionally viewed as an output rather than an outcome. We consider either of these—outputs or outcomes—as benefits. That is, there is an intellectual benefit to publishing or a programmatic benefit of a project meeting its objectives, particularly when one objective of the ALM is to foster a research relationship between the federal government and the Big Three automakers. As will be discussed later, these definitions are slightly different than those used by EERE in its Government Performance and Results Act (GPRA) reports to Congress. We do not believe there is an inconsistency; rather our work complements the GPRA efforts.

repair (U.S. DOE, 2005a).[12] The working assumptions of ALM activities are (1) that consumers will demand vehicles that are more fuel efficient, cost less to use, and emit less greenhouse gases; and (2) that these new vehicles must be comparable in every other way to more conventional vehicles. New research on lightweighting will focus on such materials as composites; advanced high-strength steel; and new alloys of aluminum, magnesium, and titanium (U.S. DOE, 2005a; Carpenter, Jr., et al., 2006b).

There is an increased effort to conduct evaluations of public R&D expenditures in order to document effectiveness, efficiency, and accountability in all federal agencies, including those with R&D functions (see, e.g., Heinrich, 2002; Behn, 2003). Leaving aside an agency's internal desire to evaluate its programs, there are numerous legislative mandates that require program review: Federal Managers Financial Integrity Act of 1982, Chief Financial Officers Act of 1990, Customer Service Executive Order of 1993, Government Performance and Results Act (GPRA) of 1993, Government Management Reform Act of 1994, Paperwork Reduction Act of 1995, REGO III of the National Performance Review of 1996, Reports Consolidation Act of 2000, and Improper Payment Information Act of 2002. There has certainly been a trend over the last 30 years to increase accountability in agencies, particularly to Congress (Roessner, 2002).

There are several uses of program evaluations. Program evaluations of R&D projects can provide informative feedback to project managers and program directors on whether R&D objectives were met. In this case, the evaluation can inform DOE managers about how well ALM projects are contributing to the goals of an effective federal government/private sector collaborative effort to introduce new, highly fuel-efficient automobiles in the marketplace. Evaluations, including those of R&D projects, also can contribute to government-wide requirements for performance-based assessments stipulated by GPRA.[13] They can detail results of federally sponsored R&D. The R&D projects evaluated in this report cover funding in fiscal years 20002004. Although this is considered a short-run evaluation, the timeframe for this evaluation is not unusual (see, for example, Link, 1995; Wessner, 2000).[14]

Once evaluators determine the objectives of a program evaluation, they can set out the methods or techniques that will measure those objectives. For example, if the effort is to monetize the outputs or outcomes, a benefit-cost analysis would be selected. Or if the interest is on knowledge gained, publications, new collaborations, and/or undergraduate and graduate student involvement may be selected. When evaluating R&D project benefits, several issues should be kept in mind: (1) benefits may not be observed for many years after a project's funding ends (Rouse, Boff, and

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[12] R&D funded by ALM falls under these broad categories: automotive aluminum; advanced materials development (e.g., aluminum, magnesium, titanium); polymer composites; low-cost carbon fiber; recycling; enabling technologies; and high-strength steels. Technology projects are designed to fall under one of three phases: concept feasibility, technical feasibility, and demonstrated feasibility (U.S. DOE, 2002; U.S. DOE, 2003; U.S. DOE, 2004c; U.S. DOE, 2005a).

[13] The efforts also contribute to DOE's performance and accountability reports, mandated under the Reports Consolidation Act of 2000, requiring agencies to provide performance information. EERE's program goals for programs including lightweighting materials can be found in section EE GG 4.02.4, page 193 (U.S. DOE, 2004b).

[14] Congress has on occasion called for evaluations of programs two years after the program was initiated (Wessner, 2000). Evaluations can be of on-going projects, prospective or ex ante (estimate of future outputs or outcomes), or retrospective or ex post (outputs or outcomes of completed projects).

Thomas, 1997; Ernst, 1998); (2) unexpected benefits may occur (Brown and Wilson, 1993; Gelijns, Rosenberg, and Moskowitz, 1998); (3) some results are difficult to monetize, e.g. increased knowledge even when a technology did not work (Nelson and Winter, 1982; Brown, 1998); and (4) benefits as well as costs may be distributed among a wide variety of interested parties with differing values, concerns, and priorities (Rouse, Boff, and Thomas, 1997). These factors grow in significance because they are observed in a diversity of R&D spheres (Gibson and Rogers, 1994; National Research Council (NRC), 1994).

Section 2 of this report begins with a review of the literature about methods that have been used to evaluate government programs generally and R&D programs specifically. The second part of this section presents the methods applied by this research to evaluate the benefits of ALM R&D projects. Here we discuss the distinction between our methodology and that reported to date by EERE. Section 3 describes the nine ALM projects in four lightweighting materials areas that we evaluated. Our earlier two reports on this issue focused on the development of benefit estimation methodology with illustration using a few aluminum and polymer composite projects supported by ALM between FY1995 and FY1999. This evaluation focuses on particular materials areas, i.e. composites, magnesium, high-strength steel, steel, and aluminum.
Section 4 presents the results of the evaluation of the nine selected projects. Section 5 offers conclusions and suggestions for future research in this area.

2. METHODS

2.1 FEDERAL R&D EXPENDITURES

The federal government outlay for non-defense R&D in 2005 was $52.6 billion (OMB, 2005). Of that, about 3.1 percent ($1,621 million) was for the U.S. Department of Energy (OMB, 2005). The Office of FreedomCAR and Vehicle Technologies (FCVT) fiscal year (FY) 2005 budget, which includes Automotive Lightweighting Materials (ALM), was about $155 million (U.S. DOE, 2004d). ALM's R&D budget for FY 2005 was about $17 million.

The estimate for FY2006 federal government outlays for non-defense R&D was $51.4 billion (OMB, 2006). Of that, 2.9 percent ($1,498 million) was for the DOE. FCVT's FY2006 budget request was slightly under $166 million (U.S. DOE, 2005c).

Public-sector financial support of R&D continues a tradition that began in the mid to late 1800s (Nelson, Peck, and Kalachek, 1967). The rationale for government R&D expenditures includes the need for solutions to problems that are of general public interest, e.g. health and national security; an urgent need for public and private sector R&D support, e.g. agriculture; and the need for science and technology research beyond a particular public sector function or industry, e.g. the National Science Foundation's support for basic research (Scherer, 1965; Nelson, Peck, and Kalachek, 1967).[15] There also is the often overlooked issue of investment in human capital development, measured through undergraduate and graduate student support or through new collaboration among researchers (National Academy of Sciences (NAS), 1999; Bozeman, Dietz, and Gaughan, 2001). Moreover, because of the high degree of uncertainty on investment returns or potential losses and long payback period, the private sector often turns to the federal government for R&D financial support (Scherer, 1965; Nelson and Winter, 1982; Gelijns, Rosenberg, and Moskowitz, 1998).

Potential benefits derived from federal R&D initiatives are quite numerous. These include advances in fundamental science (Gelijns, Rosenberg, and Moskowitz, 1998; Fitzsimmons, 2001); improvements in technologies (Ernst, 1998; Mowery and Nelson, 1999; Chapman, 1999); increased understanding and insights about policies, reduced production costs, or modifications/improvements in products and processes (Alston and Beach, 1996; Hamilton and Sunding, 1998); and facilitation of collaborative efforts (Torpey, 1994; Dietz, 1997; Bozeman, Dietz, and Gaughan, 2001; Bozeman and Corley, 2004). Finally, increased international competitiveness for U.S. firms may result from R&D projects (Papadakis and Link, 1997). ALM projects funded through FCVT have the potential to provide all these types of benefits.

The number of R&D needs related to vehicle lightweighting corresponds to the multitude of technological options to make vehicles lighter. The automotive industry admits that it needs assistance in tackling a number of these R&D needs (see United States Council for Automotive Research (USCAR, nd)). Although the automotive industry has an active R&D component, most

[15] We could also frame these within a market-failure economic context. For literature from this perspective, see, for example, Scherer (1965).

of those funds are devoted to core business issues, i.e., designing new products and new product features.

Additionally, many lightweighting R&D issues cut across the industry, making them unlikely to be funded by single companies. For example, some R&D focuses on production and processing of aluminum. Automobile manufacturers might use more aluminum in their vehicles if the cost of aluminum were lower and if aluminum parts could be made more reliable. However, the Big Three automakers are not in the aluminum business; their suppliers are. The aluminum suppliers may have fewer research dollars to conduct basic and applied R&D and may be unlikely to take such risks unless their automotive industry customers make a commitment to aluminum vehicles. Federal support for aluminum R&D helps to overcome this structural "catch-22" situation, and the national laboratories contribute unique R&D capabilities and facilities not found in the private sector.

ALM is not in the business of choosing winners and losers. All projects are jointly decided by the major partners in a collaborative effort, e.g., DOE, the national laboratories, and automotive industry partners, such as the ACC and USAMP (U.S. DOE, 2005a). The collaboration allows open discussion of critical needs and technical barriers. Then the teams select and prioritize projects to address these needs and barriers. Only those projects that could potentially benefit industry receive federal support. The intent is to carry out high-risk leveraged research using targeted research projects that eventually transfer to the auto industry or its suppliers.

Sometimes, the projects allow the United States to maintain international leadership in an important area or make up ground lost to international competitors. Additionally, the national laboratories avoid compromising the sanctity of the marketplace. The national laboratories, with the cooperation of industry, take an R&D effort only so far before allowing industry to commercialize a new material or process as the marketplace dictates. Many of the R&D projects require cost sharing from the Big Three automakers. In that case, DOE funding goes to the national laboratories, suppliers, or universities rather than the Big Three.

A systematic review of ALM R&D projects may confirm that the program is producing many of the expected benefits of federally sponsored R&D. Obviously, energy, environmental (including public health), and security benefits result from lighter weight vehicles. Other expected benefits include human capital development through support for undergraduate and graduate students, and knowledge through publications and new collaborations among researchers. Moreover, a systematic evaluation of the ALM effort can inform DOE about how ALM projects are contributing to the goals of an effective federal government/private sector collaborative effort to produce new, highly fuel-efficient automobiles for consumers.

2.2 LITERATURE REVIEW OF COMMONLY USED BENEFIT ESTIMATION METHODS FOR FEDERAL PROGRAM EVALUATION

The literature on the evaluation of governmental programs, including R&D, is quite extensive. Five basic elements of any government program should be considered during an evaluation (Hendrick, 1994):

1. inputs,
2. processes,
3. outputs,
4. short-run impacts, and
5. long-run impacts.

Under this framework, inputs are the resources used for the program (i.e., fiscal, staff). Processes are activities performed in providing services, such as number of grant applications mailed. Program outputs are immediate results of the processes (i.e., number of grant applications reviewed). Short-run impacts would be the number of projects funded and whether the project objectives were met. Long-run impacts would be the increased knowledge level (intellectual) or, as in this case, reduced energy consumption from the purchase and use of lightweighting vehicles.

Some scholars (such as Hendrick) use the term short-run *impacts*, while others use the term short-term *outputs*, considering outputs as whether the objectives of the project were met (short-run outputs can be measured in either qualitative or quantitative terms). Similarly, some scholars use the term long-run *impacts*, while others use the term long-run *outcomes*.

Other researchers have thought of program evaluation in simpler terms: evaluation of needs, processes, and outcomes (Posavac and Carey, 1985). This collapsed version of what was presented by Hendrick in essence renames inputs as needs, combines processes and outputs, and does not specifically distinguish short-term versus long-term outcomes.

When evaluating federal R&D programs, the objectives generally concentrate on measuring outputs and outcomes while acknowledging that inputs and processes are influential in outputs and outcomes. In this context of evaluating ALM R&D projects, we consider short-run outputs as those that can be measured qualitatively or quantitatively at the conclusion of the project. Outcomes are an assessment of the results of a program compared to its intended purposes and are longer term. Here, the ultimate intended purpose is the introduction and market penetration of lightweighting vehicles. Outcomes evaluation would answer the question: will lightweighting vehicles be introduced into the marketplace through technology development funded through ALM projects?

Our definitions of outputs and outcomes are supported by the program evaluation literature and by definitions included in recent federal performance legislation (see, for example, Link and Scott, 1998). Outcomes of government spending, either on R&D or in broader terms, seek to examine the impacts on the general public from expenditures of limited resources. In recent legislation on government performance, specifically GPRA, the attention centers on “measurement and systematic analysis” of whether Federal programs achieve intended objectives

(U.S. Congress, 1993, Section 4). By focusing on results, we emphasize program effectiveness and public accountability and determine whether positive outcomes are indeed accruing to the general public. In other words, is there a positive difference in people's lives from the federal government's involvement in R&D programs (General Accounting Office, 1997; Radin, 1998; NAS, 1999).

Previous studies have used numerous methods to evaluate federal R&D expenditures. A brief description of these methods follows; more information is presented in Appendix A. These methods, of course, are predicated on the objectives of the program evaluation and include:

1. Economics. Economic measures are frequently used by federal agencies in their evaluations of R&D investments. These techniques may take different forms, but the most common are benefit-to-cost ratio, internal rate of return, present value of net savings, and net benefits (e.g., a measure of rate of return). Weaknesses to economic techniques include insufficient data on benefits and/or costs, time lags between R&D funding and beneficial outcomes, marginal rate of return (how much return for an extra dollar of investment), and complexity of innovation with multiple inputs required for full adoption. Regardless of the weaknesses, economic techniques are frequently used.

2. Bibliometrics. Bibliometrics is the analysis of output from research using publication-based data. Forms of bibliometrics include publications, citation counts, presentations at conferences, publication of conference proceedings, technical reports that are publicly available (e.g., from national laboratories), and number of patents received. Limitations on use of bibliometrics as a tool include measurements of quality versus quantity in publication outlets (e.g., whether conference proceedings are peer reviewed or how well-regarded a journal is in a particular discipline), challenges in comparisons across disciplinary fields, and the increasingly important role of interdisciplinary research seeking appropriate publication outlets. Patents vary across technologies and industries, which hinders comparisons among projects.

3. Case studies. Case studies focus on the institutional, organizational, and technical factors that influence research processes, and provide in-depth insights into the success or failure of a research project. Traditionally, case studies have been used to gauge the linkages between R&D and economic innovation and to judge whether R&D projects meet policy objectives (Kingsley, 1993). Yin (1984) summarized the strengths of case studies: they address why and how an event occurs, provide a rich set of information on nonquantifiable relationships that exist among variables included in a study, and explore topics unhindered by constraining theory. Of course, there are challenges to the use of case studies. For example, it is difficult to generalize findings from case studies to a larger setting, and the rigor of the researcher can be challenged on how he or she organized and analyzed the narrative form of the information.

4. Peer reviews. Peer review is an evaluation method where an independent panel of technical experts judges R&D results. The evaluation is based on the experts' assessment of the quality of the research. Peer review is used by many federal agencies in project funding decisions, and it is gaining support for use in evaluating R&D results (Roessner, 2002). Criticisms levied against this technique include that it promotes "conservatism" and elitism or bias among reviewers (Bozeman, 1993).

5. Retrospective analyses. Retrospective analyses are long-term evaluations of federal R&D benefits. They allow a systematic linkage between funding and outcomes with special attention on spillovers and spin-offs. They are similar to case studies in that they trace historical events. As such, they can incorporate the temporal dimension mentioned elsewhere in this report. Retrospective analyses can be expensive. Moreover, such analyses cannot assist in assessing short-term outputs (NAS, 1999).

6. Benchmarking. Over the last several years, the public administration discipline has widely used this tool for evaluating performance. Appropriate indicators are compiled to judge a program (state, local, federal, or international) against its closest competitors. Hence, in this context, indicators would assess whether, for example, U.S. R&D is cutting edge. The challenge in benchmarking is for researchers to find comparable indicators and similar data-collection methods. Moreover, its use to date generally has been on programs outside the R&D field.

Each of these methods has strengths and weaknesses, as summarized in Table 2.1. Regardless of which method or combination of methods a study uses to evaluate R&D, the methodology must fit with the objectives. As Langbein noted, “most often, the controversy surrounding evaluative findings is methodological” (1980, p.3), e.g., matching the methodology with the objectives. Of course, multiple methods can be selected depending on the objectives, and more recent evaluation literature has suggested using multiple methods often combining qualitative and quantitative measures (MacRae and Whittington, 1997; Bozeman and Rogers, 2001).

The method ultimately chosen should be valid, reliable, understandable, timely, comprehensive, account for data collection and availability, and focus on controllable facets of performance. It should also be transparent to the users of the evaluation (Rossi and Freeman, 1985; Ammons, 1995; Fischer, 1995; Divorski and Scheirer, 2001). The technique should carefully delineate whether the researcher is evaluating input, process, short-run output, and/or long-term outcome.

2.3 METHODS USED FOR ALM EFFORT EVALUATION

Guided by the above review and our objective to measure short-run outputs and long-term outcomes, we continue with the three approaches to evaluate the benefits attributable to ALM projects that we used in our previous analyses (Das et al., 2001; 2002). The approaches are (1) qualitative assessment, (2) indicators adopted from the National Academy of Sciences, (3) economic analyses, including calculating a benefit-cost ratio incorporating energy, environmental, and security benefits, and reporting the person-year and cost savings to a private sector organization (including a university) from participation in the R&D effort.[16] This report adds a separate section on quantitative measures: the number of undergraduate and graduate students supported, number of patents and copyrights applied for and/or received, and software packages developed and commercialized. Where necessary we have looked at specific products

[16] We did *not* include security benefits in our first evaluation.

or deliverables from a project.[17] How each of these four fits with the methods presented in Table 2.1 is discussed below. Also elaborated on is how we increased the coverage of knowledge benefits, a qualitative assessment, based on an updated literature review. This combination of evaluation methods addresses important aspects of the benefits of R&D projects and is consistent with recommendations to use multiple evaluation criteria (Langbein, 1980; Fischer, 1995; MacRae and Whittington, 1997).[18]

There are two foci of this evaluation: The first focus area was carbon-fiber-reinforced polymer-matrix composites. The assessment of this focus area was conducted during the summer of 2005 and addressed 5 of the 23 ALM polymer composites R&D projects. The second part of the assessment, conducted during late 2005 and early 2006, assessed 4 projects focused on materials other than polymer composites: magnesium, aluminum, and advanced high-strength steel.

Table 2.1: Evaluation Methods Commonly Used

Method	Strengths	Weaknesses
Economics	Quantitative; shows monetary benefits of research.	Has not traditionally measured social benefits; productivity lag makes this difficult to measure; may not be directly traceable to inputs.
Bibliometrics	Quantitative; patents can be reliable indicator of nation's technological strength in product development.	Does not necessarily capture quality; difficult to compare across disciplines.
Peer review or subjective assessments	Well-understood by academics; can provide rigorous evaluation of research; procedure generally already established in federal agencies.	Dependent on quality of peer review panel; subjective bias may occur; may be expensive; considered elitist; conflicts of interest among researchers may occur.
Case studies	Provide extensive qualitative and in some situations quantitative in-depth insights into project; generally focuses on processes.	Difficult to generalize to broader program area; cannot compare across programs.
Retrospective analyses	Useful for identifying linkages between federal expenditure and long-term benefits.	Cannot be used as short-term evaluation tool.
Benchmarking	Comparison across programs and countries.	Difficult to find comparable measurements and data collection efforts.

Sources: Compiled from Scherer (1965); Rossi and Freeman (1985); Hyde, Newman, and Seldon (1992); Bozeman and Melkers (1993); Ammons (1995); Fischer (1995); Geisler (1995); U.S. GAO (1997); Brown (1998); Griliches (1998); Link and Scott (1998); NAS (1999); Chapman (1999); Fitzsimmons (2001); Roessner (2002).

[17] The number of graduate students supported is included in the discussion on papers published in our previous evaluations.

[18] A review of recent evaluation literature did not reveal new data collection methods, simply additional focus on measuring knowledge derived from R&D.

The qualitative assessment addresses immediate results at the project level and is in essence similar to the case studies method mentioned above. The NAS indicators address standard measures associated with the evaluation of research projects and match the peer review, benchmarking, and to some extent the case studies approach, in that they provides a qualitative assessment of the participants' view of U.S. international competitiveness. The number of graduate students, patents, and copyrights is equivalent to the bibliometrics. The benefit-cost analysis addresses long-term benefits associated with commercializing new technologies and matches the economic method.[19] Inclusion of reported person-years and cost-savings assists in an economic evaluation of the projects as well.

Since ALM projects encompass both creation of knowledge and commercialization of new technologies, these approaches are appropriate for meeting the evaluation's objectives. Each approach is outlined below.

2.3.1 Qualitative assessment

This approach focuses on the subjective judgments of project participants concerning the benefits attributable to the projects. Were the technical objectives met? Would the project have been undertaken by the private sector without federal assistance? Did the project result in improved professional collaborations? What barriers remain for wide-scale introduction of a material (e.g., carbon-fiber polymer composites, magnesium, etc.) in the manufacture of light-duty vehicles? These and other questions elicit the qualitative and somewhat intangible benefits of the R&D projects and are short-term outputs. They capture benefits that cannot be easily monetized (Roessner, 2002).

It should be noted that we have attempted to maintain consistency in our methods to permit comparison across our evaluations. However, based upon an updated literature review, we included additional inquiries on how to assess some of these subjective judgments, specifically on knowledge gained from the R&D effort. Here we were influenced by Bozeman and Rogers (2001), Rogers and Bozeman (2001), Bozeman, Dietz, and Gaughan (2001), and Bozeman and Corley (2004). Much of that work focuses on the individual R&D researchers, but it does capture a perspective on "knowledge gained" from R&D funding. Admittedly our research interest is project specific, rather than focused on individuals involved in the research. Nonetheless, this emerging focus on how the individual researcher, rather than the project, builds skills and capacity gives us an opportunity to explore knowledge-based activities that might emerge from the ALM projects. In particular, we looked at Bozeman and Corley's (2004) examination of how research collaborations evolve; knowledge value alliances (Rogers and Bozeman, 2001); and career trajectories and sustained abilities to contribute (Bozeman, Dietz, and Gaughan, 2001).

Therefore, for this evaluation, we have expanded our data collection. Previously, we asked simply if collaboration were enhanced among the research team members, keeping in mind that often a team consists of a national laboratory, a supplier, and/or the Big Three automakers. We

[19] We recognize that a retrospective analysis occurring several years after completion of an R&D project can shed light on actual market penetration used in our benefit-cost analysis.

expanded the line of questioning in this evaluation to seek such information as: had you collaborated with the other team members prior to this effort; had you collaborated with other researchers at the organizations involved in the current project; would you be willing to collaborate in the future and, if so, on what types of research.

With regard to career skills and trajectories, we asked if they envisioned future research efforts that could benefit from their knowledge gained through participation in this project. We also asked each person participating to identify what, in his or her opinion, were the five most important things learned, or discoveries made, during the research effort.

As we point out later in this section, DOE is still grappling with the issue of how to measure knowledge. We think incorporating these additional questions on knowledge and collaboration further that discussion.[20]

In the evaluation of the carbon-fiber polymer composites we sought to learn whether the project results were sufficient to make the material a viable option. For non-composite materials we sought this perspective from participants and also sought participants' evaluations of whether the results would be incorporated into the product design for light-duty vehicles. We can compare across all materials and with previous studies on the latter point.

Qualitative assessments most closely match the case studies approach from a methodological perspective. The case study approach has been used to evaluate U.S. Department of Defense research since the 1960s (see Kingsley, 1993). However, qualitative assessments are not as common in R&D evaluation among federal programs as peer review or benefit-cost analysis. We included this evaluation method because success of a project may hinge on issues that can be measured only through a qualitative approach. The qualitative assessment supports the notion of using multiple methods for evaluations. It also provides an assessment of the collaborative efforts that might evolve among the Big Three automakers, their suppliers, and national laboratories. Recall that one of ALM's goals is collaboration. Finally, the qualitative approach meets our objective to measure short-run outputs.

2.3.2 National Academy of Sciences' Committee on Science, Engineering, and Public Policy indicators[21]

Our second approach stems from a report prepared by the National Academy of Sciences' Committee on Science, Engineering, and Public Policy (COSEPUP) on frameworks for evaluation of federal R&D programs. The report was requested after GPRA passage. COSEPUP examined efforts to evaluate both basic and applied federal R&D projects. COSEPUP recognized that there are "meaningful measures of quality, relevance, and leadership that are good predictors of usefulness" of R&D results (NAS, 1999, page 2). COSEPUP noted that progress toward "specified practical outcomes" can be measured on applied and basic research, such as those

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[20] It should also be noted that in their analyses Bozeman and Rogers (2001) use traditional outputs measures, e.g., articles, patents and licenses, copyrights, graduate student support.

[21] These are referred to as National Research Council indicators in our previous reports.

R&D projects funded by ALM (NAS, 1999, page 5). The report suggested that the most effective means of evaluating federally funded R&D is through **expert review** that looks at:

- *quality* of the research program in comparison with other work conducted in the research field;
- *relevance* of the research to the agency goals; and
- whether the research is at the forefront of knowledge *or* contributing to world leadership in research fields as measured through *benchmarking* by the expert panel.

We include four measures based on the COSEPUP work:

- role of review panels in guiding and assessing the projects (acknowledging that COSEPUP intended its expert review to be at a program, rather than a project level),
- number of publications and presentations coming out of the research projects (as a proxy for *quality*,
- two indicators of *benchmarking*: (1) the participants' identification of appropriate indicator(s) for measuring leadership in the international field, and (2) participants' assessment, using the identified indicator(s) of whether the United States is leading, following, or about even in R&D on specific technology areas.

We did *not* address specifically whether the research is *relevant* to the agency goals. We simply assume that ALM activities meet DOE's goals.

As mentioned above, review panels are a standard means of assessing the quality of R&D. Peer review has long been used as an evaluation technique. It is used ex ante for project selection and ex post to determine whether a research program provided quality work. Peer review has also been strongly supported by the National Academy of Sciences for many years; thus, the reiteration of it in the GPRA context is not surprising (Roessner, 2002).[22]

There is ample precedent for using a bibliometric indicator to evaluate ALM R&D projects. Fitzsimmons (2001) documented publications, presentations, and patents in a review of PNGV's Cast Light Metals and Rapid Tooling projects. Link (1995) used publications and presentations in his evaluation of the printed wiring board joint venture and short-wave sources for optical recording projects, a joint venture funded under the Advanced Technology Program at the National Institute of Standards and Technology, U.S. Department of Commerce. The U.S. Army Research Laboratory used the number of refereed journal articles/proceedings, technical reports, and test reports in its evaluations (Brown, 1996).[23] Geisler used publications and patents in his analysis of two national laboratories (Geisler, 1995).

The benchmarking indicators are specially designed for projects that also have the potential to improve U.S. competitiveness in a particular field. Information for these indicators is collected directly from project participants and a review of project materials. These measures assess short- and long-run benefits of an R&D project. Both bibliometrics and review panels can be incorporated into the benchmarking of an indicator. Bibliometric aspects can be short-run (when

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[22] The National Research Council routinely reviewed the Partnership for a New Generation of Vehicles (PNGV), the predecessor to FreedomCAR. Moreover, this review has continued as the NRC's Board on Energy and Environmental Systems assembled a team to review FreedomCar in 2005.

[23] These evolved from a case study in response to GPRA.

the project is completed) and/or long-run (as when citations to articles indicate long-term contributions to new technology development). The role of review panels most closely matches the peer review aspects set out in Table 2.1. Hence, choice of the NAS method incorporates bibliometrics, peer review, and benchmarking.

2.3.3 Economic analyses—Benefit-cost and person-year and cost savings

2.3.3.1 Benefit-cost analysis

Our third evaluation method is an economic analysis. First, we conduct a benefit-cost analysis, which is an accepted tool in developing policy alternatives and for conducting program evaluations (Fischer, 1995). It allows for easy comparison of the benefits that would be achieved under a program and the costs of that achievement. It is transparent in that benefits and costs can be clearly identified. Hence, it is a clearly understood tool. It is also frequently used as a program evaluation method where it is important to consider preliminary long-run benefits.

There are many applications of benefit-cost methods to evaluate R&D projects. The National Institute of Standards and Technology (NIST) has used present value of net benefits, present value of net savings, benefit-to-cost ratio, savings-to-investment ratio, and adjusted internal rate of return as economic measures in its analyses. These analyses has addressed cybernetic building systems in office buildings, new standards for residential energy conservation, improved asphalt shingle for sloped roofing, and construction systems integration and automation technologies in industrial facilities (Chapman and Fuller, 1996; Chapman, 1999; Chapman, 2000).

Social rates of return on public agricultural R&D have been demonstrated for years (Alston, Norton, and Pardey, 1995; Alston and Beach, 1996). Hamilton and Sunding (1998) used a form of economic analysis (production functions under imperfect competition) on public investments in agriculture. Martin, Gallaher, and O'Connor (2000) calculated benefit-cost ratio, social rate of return, and net present value in an evaluation of NIST's standard reference materials for sulfur in fossil fuels.

Marx, Scott, and Fry (2000) calculated benefit-to-cost ratio and net benefits for NIST's investments in primary calibration services. Benefit-cost analysis has been used for evaluation of public R&D investment in forestry (Hyde, Newman, and Seldon, 1992). The Cockpit Automation Technology (CAT) program of the U.S. Air Force Armstrong Laboratory, U.S. Department of Defense, was reviewed within a benefit-cost framework (Rouse, Boff, and Thomas, 1997). Papadakis and Link (1997) used cost-benefit in measuring the impacts of new business starts-ups on plasma spray technology and in measuring new or improved products/processes with polycrystalline diamond compact drill bit knowledge from Sandia National Laboratories. Link, Teece, and Finan (1996) calculated a benefit-cost ratio in their evaluation of SEMATECH. Link and Scott (1998) estimated internal rate of return, implied rate of return, and ratio of benefits-to-costs for eight programs financed through the Advanced Technology Program, U.S. Department of Commerce.

It is assumed here that the primary benefit of the projects is to bring new technologies to the automotive market. Commercialization of the technologies, in turn, produces measurable secondary benefits with respect to reductions in energy use and emissions of air pollutants (which are explained more in Section 3). It is assumed that federal support for these projects will cause a net economic gain captured by comparing the introduction of a new DOE-researched technology to the next best alternative that was available when the new technology was introduced or that would have been available absent DOE funding. Our methodology attributes energy, environmental, and security benefits to the project. Hence, the methodology requires a baseline characterization of future energy markets without government research, and an estimation of how baseline markets will react to the new or accelerated technology, including its market penetration.

Costs considered include federal and private sector expenditures on the projects. Costs of implementing the technologies, which may include equipment costs, training costs, marketing costs, etc., are difficult to include. These costs were not available from the companies, as these costs are business confidential. It is assumed that industry demands at payback periods of two years or less on all such investments, so we ignore the first two years of the benefits for each of the technologies, arguing that these first two years' savings are needed to recoup the life-cycle capital costs of adopting the new technology (U.S. DOE, 2005b).

Calculating a Benefit-Cost Ratio

Market Penetration

The first effort to monetize benefits and costs pertains to benefits from the market penetration of new vehicles built with lightweighting materials related to the projects under consideration. This component of the method requires market penetration forecasts, both with and without the commercialization of new technologies, of the number of vehicle components and/or parts that will be produced by the new technologies, and how many vehicles will be sold each year with these new, lightweighting components. In our case, the market penetration of lightweighting materials attributable to the specific ALM project was solicited using Delphi technique. Also required is the identification of benefits attributable to each new vehicle (e.g., energy savings, environmental emission reductions, and security benefits) compared to today's vehicles, the magnitude of the benefits, and the monetized and discounted values of these benefits. These are challenging tasks that rely on informed judgments (e.g., from key participants' knowledge of market forecasting), engineering studies (e.g., for energy savings), and economic analyses (e.g., to value reductions in CO_2 emissions).

Benefit-cost Ratios

The market penetration benefits produce monetary benefit estimates, including energy, environmental, and oil security for each project. Then, the benefits are divided by the project costs to calculate benefit-cost ratios. As discussed earlier, the benefits for a project are defined as those attributed to the increased market penetration made possible by federal support, compared to that which would have been available absent DOE funding. Projects are deemed acceptable if the ratios are greater than or equal to 1.0. Projects typically need much higher ratios to be deemed successful.

2.3.3.2 Person-year and cost savings analysis

The second monetary component in our analysis pertains to what it would have cost firms participating in the R&D project to achieve the same level of knowledge gained from taking part in the R&D effort. The first set of questions in the carbon-fiber polymer composites evaluations assumes the firms ***would not*** have participated without DOE funding; hence there is a benefit from participation. We measure this by asking (1) how many person-years would your company have had to expend to achieve the same technical knowledge that you have now as a result of participating in this R&D project; (2) approximately how much *cost savings* (with full benefits) did you realize by participating in this R&D project; (3) did your company have *productivity or efficiency gains* by participating in this R&D project; (4) what percentage of productivity or efficiency gains; and (5) if your company *would* have participated in R&D on a specific project *without* financial support from the U.S. Department of Energy, what would that R&D effort have been.

If the firm ***would*** have participated without DOE funding, the firms were asked to answer the following questions: (6) how many *person-years* would it have taken you to achieve the same technical knowledge you now have with the resources noted; and (7) what would have been the *total cost* to achieve the same technical knowledge that you now have?

While the responses to question numbers 1 and 6 may be the same, the assumption is that there will be a difference. That is, we assume that the person-years gleaned from question number 6 will be greater than the response to question number 1 primarily because of the collaborative nature of these research projects. There will be a knowledge benefit to the private sector from collaboration and use of the expertise of the national laboratories, for example.

We learned from the carbon-fiber polymer composites evaluations that this line of questioning may not have been as clear as we would have hoped. We revised this line of questioning in the second evaluations.

Specifically, we asked whether a company would have participated without DOE funding. If the response was no, the participated was asked in an open-ended question to list reasons. Next we asked the participants to complete a table that sought (1) person-years committed by organization, (2) project costs committed by your organization; (3) year of introduction of product, each by *with* and *without* federal support. We then asked the respondents to calculate benefits from participating in R&D (difference between with and without federal support). We included an explanatory paragraph as an introduction to this inquiry, as well as an “example” table. We also asked the researchers to quantify the amount of productivity gains, if any, observed by their organizations from participating in the R&D effort.

This line of research is similar to Marx, Scott, and Fry’s (2000) and Link and Scott’s (1998) evaluations of NIST’s R&D efforts in primary calibration services and the Advanced Technology Program of the U.S. Department of Commerce, respectively.[24]

[24] Link refers to this as “counter-factual” in his economic impact assessment of the printed wiring board research, funded by the Advanced Technology Program (Link, 1997). We do not use that term. The distinction is that in our research we find the participants would not have engaged in this research without DOE funding or, if they would

2.3.4 Quantitative benefits

In this evaluation, we have explored separately a number of quantitative benefits: participation of undergraduate and graduate students (and what degree they were seeking), patents or copyrights applied for and received, software developed and commercialized, and other project outputs or deliverables that have been developed and may be commercialized. While these issues were touched upon in our previous evaluations, we thought precision would be brought to this benefits assessment if we addressed them separately in our analysis. Obviously there is precedent in looking at the role of students in R&D efforts, as well as other knowledge benefits that could result from an R&D effort (see, for example, Bozeman and Rogers, 2001). All these correspond to bibliometrics in Table 2.1.

2.4 NATIONAL RESEARCH COUNCIL FRAMEWORK FOR DOE BENEFITS ASSESSMENTS

Frameworks for evaluating DOE outputs, outcomes, or benefits in the R&D field have evolved since our initial report was published in November 2001. Two reports issued since then should be mentioned here with regard to how we balanced consistency in measurement for comparative purposes with our previous work and how our measures match or do not match advice given to DOE.

In DOE's FY 2000 budget, the U.S. House Appropriations Subcommittee directed an evaluation of the benefits from DOE R&D programs conducted since 1978 (NRC, 2001a). Two programs—energy efficiency, where the ALM resides, and fossil energy—were reviewed by the National Research Council (NRC). The NRC evaluation framework responded to the congressional mandate to evaluate whether "benefits . . . have accrued to the nation from the R&D conducted since 1978 in DOE's energy efficiency and fossil energy programs" (NRC, 2001a, p. 1). Specifically the evaluation conducted by NRC asked "whether the benefits of the program have justified the considerable expenditure of public funds since DOE's formation in 1977," taking a comprehensive look at the "actual outcomes of DOE's research over two decades" (NRC, 2001a, p. 2).

To answer that evaluation question posed by Congress, the NRC framework attempts to systematically capture benefits that have occurred, paying particular attention to the reality that R&D occurs within a dynamic system of marketplace, technological, and societal changes. The evaluation framework developed by NRC recognizes that benefits such as knowledge accrue even though a technology may not be introduced commercially.

NRC developed an evaluation matrix that captures three classes of benefits: economic, environmental, and security. Economic net benefits are defined as changes in market value of goods and services produced in U.S. economy under normal conditions. Economic benefits are intended to measure net economic gain captured by comparing the introduction of a new

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have, the investment would have been minimal in comparison to the total funding effort. In Link's research, he found that research tasks would have been started eventually, even in the absence of ATP support.

technology resulting from DOE research with the next best alternative available when the new technology was introduced or that would have been available absent DOE funding.

Environmental net benefits are based on changes in quality of environment. Environmental benefits occur only if there is a net improvement in environmental quality from what would have been observed without the DOE R&D program.

Security benefits are based on changes in the "probability or severity of abnormal energy-related events that would adversely affect the U.S. economy, public health and safety, or the environment" (NRC, 2001a, p. 3). This includes economic losses that might result from energy disruptions. Although traditionally thought of as unstable oil markets, there is increased concern at this point on security of the energy-supply infrastructure (Lee et al., 2003).

To capture uncertainty about commercialization of technology developed under DOE's R&D funding, NRC considered three categories of benefits and costs: realized, options, and knowledge (see Table 2.2). Realized benefits and costs are those where the technology is virtually certain to enter the marketplace, while options benefits might accrue *if* the technology is introduced commercially. Knowledge benefits occur through the R&D process even though a new technology may not be introduced and hence seek to capture scientific knowledge developed through the R&D process.

Table 2.2: NRC Matrix for Assessing Benefits and Costs

	Realized Benefit and Costs	**Options Benefits and Costs**	**Knowledge Benefits and Costs**
Economic benefits			
Environmental benefits and costs			
Security benefits and costs			

Source: NRC, 2001a, page 3.

NRC recognizes that technology development occurs within two fundamental sources of uncertainty—technological uncertainty and uncertainty about economic and policy conditions. The NRC derivative matrix is shown in Table 2.3. The framework is both qualitative (e.g., knowledge benefits) and quantitative (realized benefits). NRC applied this evaluation framework through 22 case studies, including an examination of the Partnership for a New Generation of Vehicles (PNGV), a predecessor to FreedomCAR (see NRC, 2001a, pages 32-35 and 145-151).[25] NRC *monetized* realized benefits, but not options and knowledge benefits and costs. It did, however, list *qualitatively* realized benefits, options benefits, and knowledge benefits and costs for each of the 22 case studies.

[25] It should be pointed out that for PNGV, NRC did *not* quantify benefits and costs in its case study. For reference purposes, we have included the NRC list of benefits and costs for PNGV in Appendix B of this report.

Table 2.3: NRC Derivation of Columns			
Technology Development / **Economic/ Policy Conditions**	**Technology Developed**	**Technology Development in Progress**	**Technology Development Failed**
Will be favorable for commercialization	Realized benefits	Knowledge benefits	Knowledge benefits
Might become favorable for commercialization	Options benefits	Knowledge benefits	Knowledge benefits
Will not become favorable for commercialization	Knowledge benefits	Knowledge benefits	Knowledge benefits
Source: NRC, 2001a, page 3.			

In early 2002, a conference was held on "Estimating the Benefits of Government-sponsored Energy R&D" (Lee et al., 2003). What emerged from that conference was a modified version of the NRC matrix. Specifically, there was a distinction made between past and future benefits (see Table 2.4).

Table 2.4: Conference Framework for Measuring Benefits			
	Past	**Future**	
	Realized	**Projected**	**Options**
Economic			
Environmental			
Security			
Knowledge			
Source: Lee, et al., 2003a, 2003b.			

DOE's Office of Energy, Efficiency and Renewable Energy (EERE), of which ALM is a component, adopted the following benefits framework (Table 2.5), based on the NRC report. At this point, EERE is reporting expected prospective benefits and costs for economic, environmental, and security benefits in its GPRA reports to Congress.[26] The GPRA exercise is more extensive than our work, in that it incorporates all of FreedomCAR's efforts produced from DOE models briefly described in the following paragraphs.[27] Specific DOE program benefits are estimated based on the assumption that government funding would hasten the introduction of a technology by a specific number of years. Certainly our work complements the GPRA effort, although it does not replicate it. For a more explicit comparison of the EERE framework and ours, we set the indicators we use into the NRC benefits matrix adopted by EERE in Table 2.6 (refer to Table 2.5 when reviewing Table 2.6).

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[26] See U.S. DOE, 2005c, for all of EERE's GPRA06 benefit estimates.

[27] DOE quantifies nonrenewable energy displaced in quads/year; energy expenditure savings in billions 2001 dollars per year; energy system cost savings in billions 2001 dollars per year; carbon dioxide emissions reductions in million Mtce per year; and oil-use reductions (million barrels per day). See Tables ES.3, page ES-6, and Table 4.15, page 4-20, U.S. DOE, 2005c, for quantification for several research activities that include "lightweighting materials for engines and vehicles" (page 4-18) in the calculation.

Table 2.5: EERE Benefits Matrix			
	Realized Benefits and Costs	**Expected Prospective Benefits and Costs**	**Options Benefits and Costs**
Economic benefits and costs		X	
Environmental benefits and costs		X	
Security benefits and costs		X	
Knowledge benefits and costs			
Source: U.S. DOE, 2005c, x=items currently reported in GPRA report.			

Table 2.6: Comparison of EERE Benefits Matrix and Das, Peretz, and Tonn Framework			
	Realized Benefits and Costs	**Expected Prospective Benefits and Costs**	**Options Benefits and Costs**
Economic benefits and costs		1. Energy savings 2. Reduced costs to consumers, manufacturers of material	
Environmental benefits and costs		Benefit-cost analysis focusing on energy, CO_2, CO, PM_{10}, SO_x emissions	
Security benefits and costs	Quantification of reduced demand for oil	Petroleum disruption	
Knowledge benefits and costs	1. Were technical objectives met? 2. Was this the first collaboration with partners? 3. Had there been previous collaboration with other researchers in an organization? 4. Would partners be willing to collaborate in future; if so, on what types of research? 5. In participants' opinion, what were five most important things learned or discoveries made during the R&D effort? 6. Were students involved? 7. Number of publications? 8. Were patents or copyrights applied for as a result of project? 9. Was new software developed? 10. Do outputs or deliverables from the project have the potential to be commercialized?* 11. Will research improve U.S. competitiveness? 12. Were outside review panels used? Tasks completed in evaluation that are knowledge benefits: life-cycle analysis on environmental impacts of new technology; quantification of reduced demand for oil, as well as the emphasis on participants identifying discoveries.		
*The commercialization aspect speaks directly to the NRC recognition of economic intervention in the R&D.			

Specifically, ALM, along with a host of other DOE R&D efforts, is supporting the development of technologies to improve the energy efficiency of the United States. The technological base is only one factor that determines energy use in this country. Other factors include economic activity, population, international demand for energy, and the availability and prices of energy supplies. All these factors are incorporated into an integrated analysis to estimate energy savings attributable to ALM and other DOE efforts in DOE's GPRA exercises using two integrated models—the National Energy Modeling System (NEMS) and the MARKet Allocation (MARKAL).

NEMS consists of independently developed modules that communicate energy price information through a central file system. Modules included in NEMS address macroeconomic behavior; international oil markets; residential, commercial, and industrial energy demand; transportation; electricity generation; transmission and distribution; renewable energy; and oil, gas and coal supplies. NEMS is run under a wide range of assumptions, known as cases. Cases address different levels of economic growth, oil prices, and adoption of technologies in the residential, commercial and industrial sectors.

To generate GPRA estimates, DOE also uses the MARKAL. The major inputs into this model are energy technologies and other technologies related to emissions control and energy demand and supply characteristics. The model implements an optimization algorithm to select the set of technologies that meet supply and demand constraints at the least possible cost. Like NEMS, MARKAL can be run any number of times under different sets of assumptions or cases, such as those related to changes in the material composition of light-duty vehicles. For more information on NEMS and MARKAL, see U.S. DOE, 2005c.

2.5 SUMMARY OF METHODS

Table 2.7 summarizes the four methods used in this research to assess the benefits attributable to ALM projects. The set of methods allows the assessment of qualitative factors and the development of quantitative benefit measures. All the methods have precedent in the literature as pointed out above. Together, the methods can provide comprehensive insights into the short- and long-run benefits of the R&D projects. Most important, they met our program evaluation objectives.

Table 2.7: Evaluation Methods Used in this Research	
Method	**Description**
Qualitative assessment	Assessment of participants' subjective views about the benefits attributable to the projects
Committee on Science, Engineering, and Public Policy indicators	Quantitative measurement of publications, qualitative assessment of role of review panels, qualitative identification of benchmarks to gauge international competitiveness
Quantitative benefits	Quantitative measurement of students, patents, copyrights, and software packages developed
Economic analysis—benefit-cost and market penetration	Quantitative measurement of benefits associated with the accelerated market penetration of new, lightweight vehicles whose production benefited from the research projects; measures include energy savings, air pollution emission reductions, and security benefits
Economic analysis—person-year and cost savings	Quantitative measurement of person-year savings by industry through access to federal R&D funds, quantitative measurement of cost savings accrued by industry through access to federal R&D funds.

3. AUTOMOTIVE LIGHTWEIGHTING MATERIALS PROJECTS

The single greatest barrier to use of lightweighting materials is their high cost; therefore, priority is given to activities aimed at reducing costs through development of new materials, forming technologies, and manufacturing processes. Priority lightweighting materials in ALM's R&D portfolio include advanced high-strength steels, aluminum, magnesium, titanium, and composites including metal-matrix materials and glass- and carbon-fiber reinforced thermosets and thermoplastics (U.S. DOE, 2005a).

A procedure has been developed to help facilitate the development of projects in order to help carry out high-risk leveraged research using targeted research projects that eventually migrate to the original equipment manufacturers (OEMs) or suppliers as application engineering projects. The ALM efforts are conducted in partnership with automobile manufacturers, materials suppliers, national laboratories, universities, and other non-profit technology organizations.

In this report, we concentrate on R&D projects supported during Phase II of the ALM effort, i.e., fiscal years (FY) 2000-2004. One Phase II focus in the polymer composites area has been on production of carbon fibers, which we cover in this evaluation. High-strength steel, magnesium, and aluminum have been other lightweighting material areas with significant level of Phase II effort expended and so they are also being considered in this evaluation. The fiscal year budgets for Phase II of ALM has been in the range of about $16 to $19 million per year.

The four major lightweighting materials areas considered in this evaluation encompass a large number of ALM projects, i.e., 66 projects out of about 90 major projects. The remaining projects not considered here are in the areas of titanium, metal-matrix composites, and recycling where the effort has either been too limited or projects are still in their infancy.

Table 3.1 and 3.2 list major projects funded under polymer composites and non-composite lightweighting material areas, respectively. Those projects that are 100 percent cost-shared by industry partners through the United States Automotive Materials Partnership (USAMP) are identified in these tables. The funding estimates listed for each project include both the direct funds provided by the industry partners and cost-share amounts identified in cooperative agreements, where this information was available.

The evaluation of a particular lightweighting material is based on a few representative R&D projects from that area. For example, from the list of 23 projects in the polymer composites area (see Table 3.1) covering three major material aspects (i.e., part manufacturing or polymer

Table 3.1: ALM Polymer Composite Projects Funded FY2000-FY2004						
	Project Name	Investigators	Status*	Funding ($K)		
				Prior to FY00	FY00-FY04	TOTAL
	Polymer Composites R&D or Part Manufacturing					
1†	P4 Carbon-Fiber Preform Development	ACC		4638	1802	6440
2†	Development of High-Volume Liquid Composite Molding Technology	ACC		4498	1632	6130
3†	**Automotive Composites Consortium Focal Project 3: Composite-Intensive Body Structure**	**ACC**		**152**	**4974**	**5126**
4	Focal Project 3 Design Development Offsite	ORNL		200	1025	1225
5	Study of Thermoplastic Powder-Impregnated Composite Manufacturing Technology for Automotive Applications	Delphi/PNNL	End '02	425	950	1375
6	Development of Manufacturing Methods for Fiber Preforms	Ford/ORNL		0	575	575
7†	High-Volume Processing of Composites	GM/DC/ORNL		0	1216	1216
8	Next Generation P4 Machine	ORNL		100	1825	1925
	Low-Cost Carbon Fiber					
9	**Low-Cost Carbon Fibers from Renewable Resources**	**ORNL**		**300**	**2823**	**3123**
10†	**Low-Cost Carbon-Fiber Development Program**	**Hexcel/ORNL**	**End '03**	**600**	**3438**	**4038**
11	Low-Cost Carbon Fiber for Automotive Composite Materials	Virginia Tech/Clemson Univ.	End '03	400	1409	1809
12	Economical Carbon Fiber and Tape Development from Anthracite Coal Powder	Cornerstone	End '02	300	650	950
13	Microwave-Assisted Manufacturing of Carbon Fibers	ORNL		1400	2750	4150
14	Oxidative Stabilization of PAN Fiber Precursor	ORNL		0	350	350
	Enabling Technologies					
15	**Durability of Carbon-Fiber Composites**	**ORNL**		**0**	**4900**	**4900**
16†	Creep, Creep Rupture, and Environment-Induced Degradation of Carbon and Glass-Reinforced Automotive Composites	Univ. of Tulsa/ACC		0	538	538
17†	Low Cost Test Methods for Advanced Automotive Composite Materials – Creep Compression Fixture	Univ. of Tulsa		0	250	250
18	Adhesive Bonding Technologies for Structural Components	ORNL	End '00	4100	600	4700
19	**Modeling of Composite Materials for Energy Absorption**	**LLNL/ORNL**	**End '02**	**2390**	**1970**	**4360**
20	Crash Energy Management	Ford/ORNL		2212	4442	6654
21†	Intermediate-Rate Crush Response of Crash Energy Management Structures	ORNL/ACC		0	1625	1625

Table 3.1: ALM Polymer Composite Projects Funded FY2000-FY2004						
	Project Name	Investigators	Status*	Funding ($K)		
				Prior to FY00	FY00-FY04	TOTAL
22	Energy Absorption in Adhesively-Bonded Composites	ORNL		0	1600	1600
23	Performance Evaluation and Durability Prediction of Dissimilar Material Hybrid Joints	ORNL		0	750	750
	TOTAL			**21,715**	**44,694**	**66,409**

*Fiscal year of project's end is noted only for those projects ended in FY '04 or earlier.
† Indicates the project is cost shared by industry.

Table 3.2: ALM Non-Composite Lightweighting Materials Projects Funded FY2000-FY2004						
	Project Name	Investigators	Status*	Funding ($K)		
				Prior to FY00	FY00-FY04	TOTAL
	Automotive Aluminum R&D					
1†	**Active Flexible Binder Control System for Robust Stamping**	**Ford**		**0**	**1464**	**1464**
2†	Warm Forming of Aluminum – Phase 2	DC/NCMS		0	790	790
3†	Hydroformed Aluminum Tubes	GM	End '03	0	1080	1080
4†	Electromagnetic Forming of Aluminum Sheet	PNNL/Ford		0	880	880
5†	Aluminum Automotive Closure Panel Corrosion Test Program	GM/Alcan		0	186	186
6†	Forming Advances for Aluminum Automotive Components and Applications	Alcoa	End '01	5265	135	5400
7†	Optimization of Extrusion Shaping: Aluminum Tubular Hydroforming	PNNL/Alcoa	End '01	775	1700	2475
8	Characteristics of Aluminum Tailored Blanks for Automotive Panels and Structures	PNNL/Reynolds	End '00	800	350	1150
9†	Semi-Solid Metal Forming of High-Ductilty Thin-Wall Aluminum Components	Alcoa	End '00	3631	870	4501
10†	Design and Production Optimization for Cast Light Metals	GM/AFS	End '00	6740	600	7340
11†	Die Casting Die Life Extension	PNNL/DC	End '01	4920	2400	7320
12†	Improved A206 Alloy for Automotive Suspension Components	GKS/DC		0	170	170
13	Development of the Infrared (IR) Thermal Forming Process for Production of Aluminum Vehicle Components	ORNL		0	184	184
	TOTAL			**22,131**	**10,809**	**32,940**
	Magnesium					
1	Creep-Resistant Magnesium Alloys for Die-cast Components	ORNL	End '00	325	350	675
2	Development of Magnesium Components Produced by Semi-Solid Molding with Improved High-	Thixomat/PNNL	End '00	193	0	193

Table 3.2: ALM Non-Composite Lightweighting Materials Projects Funded FY2000-FY2004						
	Project Name	Investigators	Status*	Funding ($K)		
				Prior to FY00	FY00-FY04	TOTAL
	Temperature Creep Properties					
3	Advanced Magnetherm Process for Production of Primary magnesium	Northwest Alloys/PNNL	End '01	1015	0	1015
4†	**Magnesium Powertrain Cast Components**	**GM**		**0**	**4262**	**4262**
5	Solid Oxygen-ion-conducting Membrane Technology for Direct Reduction of Magnesium from its Oxide at High Temperatures	Boston Univ.	End '03	80	150	230
6†	**Structural Cast Magnesium Development**	**GM/Penrod**		**0**	**8230**	**8230**
	TOTAL			**1613**	**12992**	**14605**
	High-strength Steels					
1	Modeling of High-Strain Rate Deformation of Steel Structures	ORNL	End '03	0	750	750
2†	Enhanced Forming Limit Diagrams	AutoSteel Partnership	End '03	0	420	420
3†	High-Strength Steel Stamping Project	AutoSteel Partnership		0	1558	1558
4†	Hydroforming Materials and Lubricants Project	AutoSteel Partnership/Dofasco		0	904	904
5†	High-Strength Steel Joining Technologies Project	AutoSteel Partnership/Ford/ Ispat Inland Inc.		0	794	794
6†	Sheet Steel Fatigue Characterization	AutoSteel Partnership/Ispat Inland Inc.		0	466	466
7	Strain Rate Characterization	AutoSteel Partnership/GM.		0	358	358
8†	High-Strength Steel Tailor-Welded Blanks	AutoSteel Partnership/US Steel Group/DC	End '03	0	438	438
9†	Tribology	AutoSteel Partnership/GM		0	334	334
10†	**Lightweighting Front Structures**	**AutoSteel Partnership**		**0**	**3082**	**3082**
11	Evaluations of the Effects of Manufacturing Processes and In-Service Temperature Variations on the Properties of Transformation-Induced Plasticity Steels	PNNL		0	75	75
12	Development of Advanced Tools for Energy Management	ORNL		200	750	950
13†	Lightweighting Closure Panels Project	ASP/Ford		0	358	358
	TOTAL			**200**	**10287**	**10487**

* Fiscal year of project's end is noted only for those projects ended in FY '04 or earlier.
† Indicates the project is cost shared by industry.

composites R&D, low-cost carbon fiber, and enabling technologies), the following five projects were selected for evaluation. These projects are noted in bold text in Table 3.1.

1. Composite-intensive body structure for focal project 3
2. Durability of carbon-fiber composites
3. Low-cost carbon fibers from renewable resources
4. Low-cost carbon-fiber development program
5. Modeling of composite materials for energy absorption

Similarly, the following four projects were selected for evaluation in the three remaining lightweighting materials areas (see Table 3.2):

1. Active flexible binder control system for robust stamping (aluminum)
2. Lightweighting front structures (advanced high-strength steel)
3. Magnesium powertrain cast components (magnesium)
4. Structural cast magnesium development (magnesium)

The projects selected from the polymer composites area cover the range of research project areas, funding sources (e.g., cost sharing from industry), and project status (e.g., completed or on-going). The projects selected for evaluation address the primary concerns of DOE and the automakers. In two cases, the concern is the cost of replacement materials for automobiles. Due to concern about the high cost of carbon fibers, and as a means to increase their viability to the automakers, two projects (numbers 3 and 4—*low-cost carbon fibers from renewable resources* and *low-cost carbon-fiber development program*) were selected. Similarly, two projects (numbers 2 and 5—*durability of carbon-fiber composites* and *modeling of composite materials for energy absorption*) fall under the category of enabling technologies, focusing on durability and safety areas, respectively. The remaining project—*composite-intensive body structure for focal project 3*—covers the area of polymer composites manufacturing R&D and is 100-percent cost shared by the industry. In addition, it covers technology commercialization.

The two projects considered under low-cost carbon-fiber enabling technologies illustrate the difference in nature of project partners, i.e. national laboratory versus industry collaboration with national laboratories. Only two projects, (numbers 2 and 4—*durability of carbon-fiber composites* and *low-cost carbon-fiber development program*) had been completed at the time of the evaluation.

Four of the polymer composites projects fall under the technical feasibility stage, that is, a specific idea is being developed or something new being created to address a need. Only one project (number 4—*low-cost carbon-fiber development program*) moves a technology from a test of feasibility to a demonstration of technology use. The following paragraphs provide more detailed descriptions of these five projects.

On the other hand, the four projects selected under the non-composite materials area mainly involve material application in a specific demanding area of automotive applications. Magnesium projects selected not only are the two largest projects funded in this material area, but both are nearing completion and have had the greatest industry participation. Because aluminum is a relatively mature automotive material, the focus of the selected aluminum project has been the stamping issue and the application of results to aluminum and other competing lightweighting materials. Despite the introduction of more advanced high-strength steels in light-duty vehicles, challenging areas such as joining, failure, and structural part manufacturing continue. Most of the ALM projects have only been initiated to address these issues during Phase II of the program in coordination with the Auto/Steel Partnership. Only one project—*compositei intensive body structure for focal project 3*—selected in this area is a technology validation project and is the beneficiary of other projects supported in this area.

3.1 POLYMER COMPOSITE PROJECTS

3.1.1 Composite-intensive body structure for focal project 3

The project goal is to design, analyze, and build a composite-intensive body-in-white, while meeting structural and production objectives such as high-volume production techniques yielding 60 percent mass reduction at cost and structural performance parities with steel. This project is a part of the validation activity (called focal projects) demonstrating one of ALM's goals of reducing the lead time to bring new technology into the marketplace. These projects are jointly done by DOE and the U.S. Council for Automotive Research's (USCAR) Automotive Composites Consortium (ACC), USCAR's collaborative, pre-competitive consortium for composites. Focal projects center on bringing together technology developed by each of the ACC working groups. In this case, the emphasis is on carbon-fiber-reinforced polymer composites and the use of hybrid materials, faster manufacturing processes, design optimization including crash worthiness, and rapid joining methods.[28]

During Phase 1 of this project, the design of a composite intensive body-in-white (BIW) was optimized using finite-element analysis, the structure meeting or exceeding all design requirements including the mass reduction target of 60 percent. Construction of the complete BIW is planned after one BIW part is built to demonstrate high-volume processing methods, including the component as well as the needed assembly fixtures.

The single BIW body side part (i.e., initially both inner and outer portions of B-pillar only) was considered before the construction of a complete BIW, for which initial preforming and molding trials were successfully completed. Technical support for preforming and molding of the part was based on the two ongoing ALM funded projects, i.e., development of manufacturing methods for fiber preforms and high-volume processing of composites. The preforming results obtained to date suggest that a 1.5-mm part thickness at a fiber volume fraction of 40 percent is extremely challenging and may be at or beyond the current process capability.

A flow model for the injection-compression molding of the B-pillar has been developed which could be used as a design tool assist in optimizing the injection locations for the full-body side mold. Challenging issues, such as liquid molding of variable thickness sections (1.5-8.0 mm) at high volume fractions of reinforcing fibers and methods for joining the inner and outer sections of a panel, were successfully addressed. A learning tool was designed to conduct the processing and materials research necessary to enable this part production. Structural testing of these B-

[28] An earlier focal project 2 (1995-1999) demonstrated the feasibility of producing glass-fiber-reinforced polymer composite pickup truck boxes at a rate of one every four minutes.

pillars is currently underway including an evaluation of its bond quality in terms of agreement between simulations and test results.

Cost assessment of a complete carbon-fiber reinforced polymer (CFRP) body side inner using powdered preforming and structural reaction injection molding technology indicates a part cost of more than $5 per pound, compared to $1-$2 per pound generally assumed for the conventional steel part (Das, 2003). There exists a substantial part cost reduction potential particularly with a lower carbon-fiber cost. However, the viability of CFRP BIW technology can only be determined with a complete BIW cost assessment which captures the part consolidation and the net-shape processing characteristics of composites.

3.1.2 Durability of lightweighting composite structures

This is one of ten projects supported under the enabling technologies focus research areas; it has the largest budget incurred to date and is being carried out with close oversight by ACC. This project is a follow-on to an earlier, similar high-funding-level project focusing on glass-fiber-reinforced polymer composites. The focus of this project is to develop experimentally-based, durability-driven design guidelines to ensure the long-term (15-year) integrity of representative carbon-fiber-based composite systems in large structural automotive components.

Durability issues being considered include the potentially degrading effects of cyclic and sustained loadings, exposure to automotive fluids, temperature extremes, and low-energy impacts from such events as tool drops and kick-ups of roadway debris on structural strength, stiffness, and dimensional stability. The general project approach has been to first replicate on-road conditions in laboratory specimens to generate data to form the basis for developing correlations and models. These correlations are then used to formulate design criteria.

The durability assessments considered the design temperature range to vary from a minimum of -40° C to a maximum of 120° C, and a maximum exposure time of 5,000 hours in an environment ranging from distilled water to eight most commonly used vehicle fluids. The simulation of impact damage was done using pendulum drop tests to represent such things as tool drops, while an air gun with a small projectile was used to represent the other extreme, such as kick-ups of roadway debris.

Both directed, continuous-fiber-reinforcements (i.e., reference ±45° crossply and quasi-isotropic) as well as random, chopped-fiber reinforcements having the same thermoset urethane matrix were considered.

Other durability issues addressed included the effects on deformation, strength, and stiffness of cyclic and sustained loads, operating temperature, automotive fluid environments, and low-energy impacts. Basic short-time properties used to develop design criteria include tensile, compressive, shear, and flexural strength. Guidance has been developed for design analysis, time-dependent allowable stresses, rules for cyclic loadings, and damage tolerance design guidance. The design criteria documents from this project have been published.

A more recent focus has been on the investigation of quasi-isotropic carbon-fiber-reinforced thermoplastic (e.g., polyphenylene sulfide (PPS)) materials for structural applications, an area where durability issues are generally more significant. Crystallinity changes of thermoplastic materials can result in significant changes in the mechanical behavior of composites containing them, particularly with respect to matrix-dominated properties such as compressive strength and creep.

Durability-based design properties and criteria for these types of materials for possible automotive structural applications are yet to be developed. These will be prepared after testing beyond baseline room-temperature tensile and compressive properties are completed. The durability data on chopped carbon-fiber composite have been used in the planning and analysis of *focal project 3* discussed above.

3.1.3 Low-cost carbon fibers from renewable resources

This project focuses on the development of carbon fibers from high-volume, low-cost, renewable or recycled sources to reduce precursor and processing costs for the large-scale automotive applications. Production of low-cost, high-volume, carbon-fiber precursors focus on the simultaneous development of processes for making the feedstock fibers, as well as downstream processing techniques. Melt-spun polymer blends of Kraft lignin consisting of 20-30 percent wood and woody biomass, which is commercially available as a byproduct of the U.S. paper industry, was considered as one of the viable options that could greatly increase availability of carbon fiber and thereby decrease its price.

The use of lignin and other non-nitrogenous feedstocks also helps in the elimination of cyanide emissions during furnacing. Gasification, which is being evaluated as an alternative to current lignin combustion processes, could provide significant amounts of lignin as the precursor for the low-cost carbon fiber.

MeadWestvaco hardwood Kraft lignin with a narrow melting point range was blended with small amounts of a variety of polyolefins and polyesters (including pre-consumer recycled polyester) and was melt spun to produce single fibers which were then processed using conventional furnacing sequences to yield carbon fibers. A two-step fiber spinning method was used, i.e., pellet extrusion followed by fiber extrusion to reduce significant voids in the fiber. The yield of carbon fiber obtained was around 50 percent, consistent with data obtained commercially for lignin-based activated carbon. Subsequently, larger amounts of lignin-blend feedstock melt were successfully extruded as a 28-multifilament tow using a near-commercial twin-screw Leistritz extruder. Industrially tractable solutions were developed to address encountered technical problems of a combination of particulates in lignin and evolution of gas from lignin during spinning of small lignin fiber tows.

A combination of plasma treatment of the fiber surface and silanation with reduced environmental impacts has also been established for the dense, smooth-surfaced lignin fibers to increase its resin compatability necessary for actual composites manufacturing. A successful demonstration of the use of this material in small epoxy resin-fiber composites has also been completed and an extension to evaluate methods for producing high-quality lignin-based feedstocks for low-cost production of automotive carbon fiber resin composites has been proposed. The major focus during the fiscal year (FY2006) is toward the development of a lignin feedstock specification including basic rheology for extruding and winding lignin bundles with improved handling characteristics to facilitate industrial production of carbon fibers.

A recent cost assessment of potential new low-cost carbon fiber manufacturing technologies indicates a significant cost reduction potential for the low-cost carbon fiber precursor lignin (Kline and Company, 2004). In addition to the use of lignin precursor, microwave-assisted plasma (MAP) to aid in the reduction in residence time for carbonization will help in lowering the carbon-fiber cost by 37 percent. A higher reduction of 45 percent in carbon-fiber cost can only be achieved with the use of microwave oxidation (lowers oxidation stabilization cost by replacing large electric ovens) besides MAP. Although these technologies offer a significant cost reduction potential, it is not low enough to achieve the DOE cost target range of around $3 per pound for large-scale automotive applications.

It is anticipated that with the formalization of partnerships between Eastman Chemical Company and MeadWestvaco, the formal transfer of technology for a large scale production of carbon fiber from Kraft lignin blend feedstocks and associated intellectual property will be initiated during 2006.

3.1.4 Low-cost carbon fiber development program

The objective of this project, performed by Hexcel Corporation (one of the largest carbon-fiber manufacturers), was to develop technologies needed to produce a low-cost carbon fiber for automotive applications at a cost of $3.00 to $5.00 per pound in quantities greater than one million pounds per year, with tensile strength greater than 400 ksi, modulus of greater than 25 Msi, and strain-at-failure greater than 1 percent. The focus of this project was on the precursor type and its stabilization process, two major contributors to the carbon-fiber manufacturing process. Hence, not only were alternative low-cost precursors considered in this project, but also the development of precursor processing methods other than conventional thermal analysis methods for producing carbon fiber from these low-cost precursors.

Both conventional polyacrylnitrile (PAN)-based and non-PAN-based precursors were considered. The former included large tow benchmark (>24,000 filaments as the benchmark), textile acrylic, chemical modifications, acrylic fibers spun without solvents, and radiation-treated. Non-PAN precursors were mainly polyethylene, polyprophylene, polystyrene, and polyvinyl chloride.

Of these, commodity textile acrylic 28,000 tow with chemical modification or radiation pretreatment were down-selected as the most promising technologies meeting the program targeted properties and estimated cost predictions. Both of these technologies reduce carbon fiber manufacturing costs by accelerating the rate-limiting stabilization stage in the carbonization process of the carbon fiber manufacturing technology. Other technology options were not further considered because of technical, environmental, and cost issues. Of the non-PAN-based precursors, linear low-density polyethylene (LLDPE) demonstrated the most promise but, due to issues of sulfuric acids recycling and precursor availability, additional development efforts would be required.

Detailed manufacturing cost models for the down-selected technologies were also developed, and found to lower the carbon-fiber cost compared to large tow precursor (baseline) by $1.50 per pound and $1.25 per pound for chemical modification and radiation treatment, respectively. Additional improvements such as higher line speed, longer production cycles, and higher conversion yield etc. are needed to achieve a desired cost target of less than $5.00 per pound. Engineering feasibility studies for a large-scale production line including the economic analysis to predict production costs were completed for the two down-selected technologies; these studies concluded that a further reduction in product cost should focus on in the precursor and capital-cost reductions and fine tuning of other cost contributors.

This project also has been supporting several ongoing carbon fiber technology programs, e.g., Oak Ridge National Laboratory (ORNL) and Delphi's Advanced Composite Support Structures project, a short-term (1-year) project to develop carbon fiber roving for the programmable powdered preforming process (P4) to meet the immediate needs of the ACC development programs. A follow-on cost-shared project (i.e., Phase II) has been proposed to scale-up and verify the defined technologies and integrate them in ongoing automotive research activities by ORNL and the ACC.

3.1.5 Modeling of composite materials for energy absorption

This project is continuation of an earlier project but with the current focus on carbon-fiber-reinforced polymer composites instead of glass-fiber-reinforced polymer composites. ORNL and Lawrence Livermore National Laboratory are the project partners.

The objective of this project was to develop analytical and numerical tools that efficiently predict the behavior of carbon-fiber-based components in vehicular crashworthiness simulations. An understanding and quantification of the basic deformation and failure mechanisms active in carbon-fiber materials during vehicular crush conditions was the major thrust of this project. Numerical modeling validated by experiments dealt exclusively with automotive materials: braided, textile, and chopped random-fiber architectures. These modeling tools are intended to decrease the automotive design process time and cost by reducing component testing and to increase the simulation accuracy of carbon-fiber-reinforced structures. The developed tools are used in conjunction with existing crash simulation software.

A three-dimensional micro-mechanical-based finite deformation constitutive model has been developed and implemented into the nonlinear finite element code which attempts to replicate progressive damage in carbon-fiber polymer composites and is intended for use in automotive crashworthiness applications. The finite element approach was also used to extend in several ways the assumed enhanced strain formulation to replicate cracks numerically in the braided composites, and new methods for characterizing critical material parameters for modeling of crushing of discontinuous fiber composites were developed. Specifically, the tow-level failure mechanism impacting the overall braided carbon-fiber polymer-composite properties was characterized. Similarly, a damage model for braided carbon-fiber polymer composites incorporating the compressive and tensile damage mechanisms within the tow-level constitutive model was developed. Lastly, the fundamentals of damage and failure of disordered media and linking them to the material model for random carbon-fiber polymer composites were also investigated.

This approach was then applied to (1) develop methods for modeling and characterizing the structure of random carbon-fiber materials such as those made by programmable powdered preform processing (P4) manufacturing (another research area supported by the ALM effort) and (2) determine the implications of the material structure on mechanical properties. An experimental program has also been defined and initiated in support of developing analytical material models for predicting the crashworthiness of chopped carbon-fiber composite structures, where the focus has been on running basic material property tests at quasi-static and dynamic loading rates. The project was terminated during fiscal year 2002, but further work has been proposed to validate and modify the present models against experimental results. The project does not include the ongoing complementary composite crash energy project led by Ford Motor Company, the objective of which is to develop and demonstrate the technology required to apply production-feasible structural composites in crash and energy management applications.

3.2 NON-COMPOSITE LIGHTWEIGHTING MATERIALS PROJECTS

3.2.1 Active flexible binder control system for robust stamping

One of the challenges currently faced by lightweighting materials (aluminum and magnesium alloys) and high specific-strength materials (advanced high-strength and stainless steels) for widespread automotive applications is formability. Parts made from these materials lack dimensional control because of the significant amount of springback that they produce after forming. This project focuses on the development of flexible binder control technology in conjunction with innovative tool designs and closed-loop control to produce robust processes for stamping these materials. This technology uses computer simulation and process optimization to predict optimum binder-force trajectories that can be entered into programmable hydraulic cushions to control binder actions in mechanical and hydraulic presses. This project was initiated in FY01 as a part of automotive aluminum R&D and has numerous participants from more than a dozen organizations including the Big Three OEMs, aluminum and steel manufacturers, stamping press manufacturers, and die makers.

To conduct open-loop control demonstration of the flexible binder control technology, researchers retrofitted an existing supplier press and also are building a more robust and smaller unit to accommodate a generic tool for industrial stampings at the University of Stuttgart (IFU). Using the retrofitted system, tryouts conducted on the GM liftgate using three sheet materials (i.e., bake hardenable steel, dual-phase steel, and aluminum alloy) have been successful. The IFU unit has state-of-the-art cylinders, valves, and controls thereby providing a large collection of advanced features. It accommodates three types of sensors for use in closed-loop control of the binder in a mechanical press environment and testing of this unit using different types of sheet materials is currently underway. In addition, adaptive simulation and optimization methods, coupled with finite element method simulation were developed and used to predict optimum, constant, and variable blank holder force trajectories in single and multipoint cushion systems to reduce thinning and springback in the IFU part, the fuel tank shield, the S-rail and the General Motors structural rail. Variable blank holder force profiles increase the formability of stamping parts and test runs for the IFU pan and General Motors liftgate are being considered in one of the project future plans.

3.2.2 Lightweighting front structures

As a partnership between Auto/Steel Partnership and OEMs, the project objective is to benchmark, develop, and document proven solutions that will balance the interaction of material, manufacturing, and performance of lightweighting automotive steel front structures. This project is one of the many equally cost-shared projects with the Auto/Steel Partnership. The initial focus has been on the automotive front end systems solutions utilizing advanced high-strength steel (AHSS) designs that address high-volume manufacturing and assembly with a weight savings potential of at least 20%. During Phase 1 of the project, two different configurations of the original ultralight steel auto body (ULSAB) vehicle were optimized in which 12 kg (or 5.1%) mass reduction was achieved under one configuration. A new bumper design and various rail designs using AHSS materials (e.g., DP 800) and manufacturing techniques such as stamping and hydroforming were developed as the automotive front-end system solutions showing the potential for the mass savings that exceeds the 20% target. Although the hydroformed design had the potential for more mass savings, the stamped design (which included tailor-welded stampings) was considered for the final vehicle build having less manufacturing concerns and so more acceptability in the production environment. A total of 14 competitive vehicles were benchmarked for rail design and architecture. Formability simulation of the stamped design and the required prototype tools and dies have been completed. Correlation of the vehicle crash data with analytical results was completed for during the FY05.

3.2.3 Magnesium powertrain cast components

This project is a relatively large project, consisting of numerous team members both from OEMs and suppliers as a part of US Automotive Materials Partnerships (USAMP). It has made excellent progress since its inception in 2001. The objective of this project is to demonstrate and enhance the feasibility and benefits of using magnesium alloys in place of aluminum in structural powertrain components, thereby achieving at least 15% weight reduction of the cast components. Through the finite-element analysis design activities, cost modeling, and extensive alloy casting and testing, researchers quantified the technical and economic requirements of the V6 engine identified which of the newly developed, high-temperature magnesium alloys best met those requirements for each cast component.

Phase I of the project was successfully completed by identifying, benchmarking, and developing a comprehensive engineering design database of the potentially cost-effective, high-temperature magnesium alloys which was used to select the alloys that are most suitable for the magnesium components. An ultra-low-weight Duratec V-6 engine containing four potential magnesium components (i.e., cylinder block, bedplate, structural oil pan, and front engine cover) was designed using the most suitable low-cost, recyclable, creep- and corrosion-resistant magnesium alloys. The pair-wise analysis methodology was used for the selection of one alloy for each component by identifying the most important criteria and categories for qualitative as well as quantitative rating of the candidate high-pressure die casting and sand-casting alloys. Design revisions of the engine components based on their selected respective alloys were done with a particular emphasis on the optimized noise, vibration, and harshness (NVH) performance for the oil pan and the front engine cover. Design and building the tools for high-pressure diecasting has been followed by defining an engine test matrix to measure the performance and durability of the magnesium-intensive engine in dynamometer testing. Fundamental scientific challenges (e.g., phase equilibria and computational thermodynamics, alloy recycling etc.) of using magnesium alloys and casting processes in powertrain components, both within the ongoing project and for more advanced powertrain components, were also identified during the execution of Phase I of this project. This activity led to the initiation of five projects in 2005 to address the areas of critical scientific needs, considered necessary for the development of understanding to fully implement magnesium alloys in powertrain components.

This project has been a true technology validation towards the high-temperature creep-resistant magnesium alloys' application in powertrain cast components. The final project report is expected to be completed during FY07 and will address the dynamometer testing, teardown, and analysis of the engines conducted during the course of the project.

3.2.4 Structural cast magnesium development

The focus of this project has been on the same lightweighting material, magnesium as was in the case of the previous project with a mass reduction potential of 25-35% compared to aluminum. Cast magnesium structures have the potential to reduce 100 kg of vehicle mass, so development and demonstration of technically feasible casting processes would allow a significant level of fuel consumption and emissions benefits. Development of the science and technology necessary to implement front structural cradles (with two different magnesium casting processes) while interfacing with other concurrent magnesium programs proposed for the U.S. automotive industry was considered in this project. These components offer all of the difficult manufacturing issues such as casting process (high-pressure die, semi-solid, low pressure, and squeeze etc.) and joining, along with harsh service environment challenges, such as corrosion, fatigue, and stress relaxation associated with fasteners. The project team consisted of a fairly large number of participants from numerous organizations, including 3 OEMs, three national labs through cooperative research and development agreements (CRADA), and 34 companies from the casting supply base. National labs have been mainly involved in model development besides radiographic analysis of production parts and test samples.

An existing in-production aluminum engine cradle has been redesigned for two different magnesium casting processes, i.e., high-pressure die casting (HPDC) and low-pressure permanent mold. Utilization of upfront computer modeling used for both of these processes resulted in significant time and costs savings and eliminated casting defects in the initial castings. Weight savings in prototype castings has been estimated to be around 35% compared with the current aluminum production part. Several hundred HDPC production prototype castings have been distributed to the project participants and to the General Motors Corvette Team for the vigorous testing procedures to determine what action (if any) will be required to meet the timing date of Job 1 for the 2006 production year. HPDC design guide has been developed and cost was one of the criteria included in the final part design. In fact, the 2006 model year Corvette Z'06 has a magnesium engine cradle. Consideration of an alternative low-pressure permanent mold casting process for casting the same cradle is underway which can then be applied across a large type of magnesium castings in the magnesium industry. The investigation of producing the same casting by the two different processes has a great potential to enable existing aluminum companies to expand their operations into magnesium, without huge capital and facility expenditures. Rigorous bench tests of HDPC magnesium cradles involving actual vehicle road tests will continue with an anticipation of a potential market for 45,000 vehicles by 2007 production year. Development of sensors, database, and practical casting applications developed by this project will continue with the industrial participants.

4. RESULTS

4.1 QUALITATIVE ASSESSMENT

This approach entails contacting key project participants for subjective assessments of the benefits of each project. The information-gathering process is described immediately below. The results for each project are presented in Sections 4.1.2 through 4.1.7.[29] A summary of the overall results of the qualitative assessment is presented in Section 4.1.8.

4.1.1 Information gathering

For the assessment, we interviewed key participants in each research project via e-mail (except one, who preferred a telephone interview) following a standard set of prepared questions. Key participants are defined as project managers or key researchers making an intellectual contribution to the R&D effort. These persons possess detailed yet strategic knowledge about the projects. Most of the R&D projects consisted of teams at a national laboratory, private-sector firm, or university. One R&D project involved two national laboratories. It should be noted that there were some participants who played a key role in their specific task, but may not have been actively involved in every project aspect. Interviewing those directly involved in the project design and implementation has been used in other R&D assessments (see Rouse, Boff, and Thomas, 1997).

To confirm key members of each project, we first reviewed the ALM progress reports where, for each project, a list of researchers is provided (U.S. DOE, 2002, 2003, 2004c, and 2005a). Next, we looked at the authors/co-authors of publications cited in the ALM progress reports. We infer that if a person authored or co-authored a report or if the researcher is listed in the ALM progress reports, he or she is a key research participant. We then provided that list to the R&D project manager, principal investigator, or the field technical manager for each R&D project for confirmation. In some cases, an introductory e-mail from the project manager or principal investigator was sent to the participants announcing the evaluation. The project manager or principal investigator also may have sent follow-up communication encouraging the participants to respond.

In cases where only an organizational name rather than an individual researcher was referenced in the ALM progress report, the principal investigator was asked to make a determination on whether the organization made an intellectual contribution to the project, or simply was the source of a piece of equipment. If the organization served as a key research participant, the R&D project manager, principal investigator, or field technical manager was asked to provide name and contact information.

We worked from this final list to contact persons. In some situations, researchers left the organization prior to the evaluation. In another case, a participant at one university passed away

[29] Accomplishments for each project can be found in the ALM progress reports (DOE, 2002, 2003, 2004c, and 2005a).

after the completion of the task. Finally, there was a case where one investigator was cited in only one year's ALM progress report (rather than all years we reviewed). During our discussions with the field technical manager and principal investigator, it was revealed that this person served more as a "reviewer" rather than a researcher (due primarily to this person's research activity in another R&D effort). In another R&D project, we had an organization identified initially but their staff, according to the technical field manager and principal investigator, were not intimately involved in the research. That organization was dropped.

We sent each key participant, as identified through the above process, a set of questions. A follow-up message was sent to those not responding two to three weeks after initial contact. Third and fourth contacts were made in some instances.[30] As noted above, in some instances, the project manager or principal investigator followed-up with the participants.

In all cases, the key participants were assured confidentiality and were provided a list of the institutions conducting the evaluations. Copies of our previous reports were also offered to participants so they could review examples of how their responses would be presented in the final report. Because confidentiality is assured in this research effort, no responses in this report are attributed directly to any interviewee. Instead, the responses are phrased in more generic terms.

Our participation rates ranged across projects from 40 percent to 100 percent (see Table 4.1). We recognize that the sample size is small. This is simply based on the fact that there were few people involved with some projects. The literature recommends interviewing only those directly involved in the project (e.g., see Rouse, Boff, and Thomas, 1997). It does not seem to be worth the cost to interview people who were unlikely to have anything of value to contribute to the evaluation of the projects.

Methodologically speaking, the small sample size is not an issue of concern. We approached the interviews from a case-study perspective. We had no intention of using (and did not use) the interview data to statistically test any hypotheses or to generalize the interview results to other projects or programs. Thus, there were no methodological requirements for large sample sizes.

4.1.2 Composite-intensive body structure development for focal project 3

The principal investigator for the project is from General Motors' research and development center; researchers are from the Massachusetts Institute of Technology; Universities of Delaware, Michigan, and Texas; and Oak Ridge National Laboratory (ORNL). The ACC also was actively involved. The final list of persons to contribute to the evaluation was determined through conversations with the principal investigator and the evaluation team after a review of the ALM progress reports (DOE, 2002, 2003, 2004c, and 2005a).

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[30] In some cases, we made eight attempts to reach the participant.

Table 4.1: Response Rates			
R&D Project	**Number Contacted**	**Number Completed**	**Response Rate**
Composites			
Composite-intensive body structure for focal project 3	11	6	55%
Durability of carbon fibers composites	12	8	67%
Low-cost carbon fibers from renewable resources	7	6	86%
Low-cost carbon fiber development program	6	6	100%
Modeling of composite materials for energy absorption	5	2	40%
Non-Composite Lightweighting Materials			
Active flexible binder control system for robust stamping	7	6	86%
Lightweighting front structures	5	3	60%
Magnesium powertrain cast components	41	29	71%
Structural cast magnesium development	28	20	71%

Although only 50 percent of the respondents viewed the technical objectives as being met, those indicating "no" or "not sure" mentioned that the project was still on-going or that the researcher was only involved in one task and was uncomfortable speaking for the entire project. All participants agreed that the project yielded knowledge; knowledge gains are listed in Table 4.2.

Table 4.2: Participants' Opinions on Knowledge Gains from R&D Effort—Composite-Intensive Body Structure Development for Focal Project 3	
Respondent No.	**Knowledge Gains**
1	(1) structural analysis and design capability for chopped carbon composites, (2) identification of mass reduction potential, (3) improved manufacturing process for high volume production needs of auto industry, (4) joining methodology for carbon composites, (5) technical cost modeling shows cost competitiveness of composite structures
2	(1) mold geometry required to permit uniform preform fabrication, (2) limitations to the thickness that can be preformed, (3) issues associated with performing carbon fibers, (4) variability of material properties of carbon-fiber composites made with the preform method
3	(1) modeling techniques, (2) improved testing methods, (3) development of advanced numerical schemes and methods, (4) improved predictive methodologies and damage simulation, (5) recommendations and insights into bonding of composites and multi-phase material systems
4	(1) design of the manufacturing process, (2) pressure field, (3) material property characterization

Collaboration had been established among research team members assigned to this project from the auto industry, ACC, and ORNL prior to this research endeavor. There had also been collaboration with other researchers at these organizations. The universities did not have a prior working relationship with the team members. Regardless, all respondents expressed an interest in future collaborations on numerous topics, such as: research to resolve the range of barriers remaining for the implementation of light-weight materials, modeling, high-strain-rate structural and materials responses, and ultra-high-strain-rate measurement. Fifty percent felt that future career endeavors would benefit from participation in this R&D project.

One private-sector firm had used the results from the R&D project for a new product (body side). Two contributors replied that the aerospace industry *has* benefited from the research findings, while 67 percent (N=4) viewed the aerospace and sporting goods industries as *potentially* benefiting from the R&D endeavor. Another participant mentioned the sporting goods industry.

Only one respondent thought his organization would have pursued research in this arena without funding from DOE; none of the other organizations would have. Risk was cited as the reason for not participating without DOE involvement.

Thirty-three percent of those contributing to this evaluation commented that they thought the results were sufficient to make carbon fibers a viable option for the automotive industry. When asked in an open-ended format to list the barriers of low-cost carbon fibers in the manufacture of light-duty vehicles within the U.S. automotive industry, four respondents cited cost. Other barriers listed relate to manufacturing and/or performance issues including durability, recycling, incorporation into rest of manufacturing structure, consistency in manufacturing process, and changing the corporate culture of the auto industry to embrace a new component (e.g., composites rather than metals).

4.1.3 Durability of carbon-fiber composites

This project involved researchers at ORNL, the University of Tennessee (UT), and members of the Automobile Composites Consortium (ACC). Eighty-eight percent of the respondents felt that the technical objectives had been met; 12 percent were not sure. The same percentage—88 percent—of respondents indicated that knowledge gains resulted from the R&D effort, while 12 percent were not sure. Five respondents identified specific areas of knowledge gains, as reflected in Table 4.3.

With regard to collaboration, members of the ACC had collaborated previously with some of the ORNL researchers assigned to this research effort. One respondent had participated in past years with *other* researchers at ORNL on a separate fiber carbonization project. Although not every researcher from ORNL, UT, and ACC had worked together as a team, collaboration among some participants in general had been established prior to this project.

Of those responding to the question on willingness to collaborate among the remaining organizations in future research efforts (N=6), 86 percent of the respondents indicated a willingness to collaborate among the remaining organizations in future research efforts. Fourteen

Table 4.3: Participants' Opinions on Knowledge Gains from R&D Effort— Durability of Carbon-Fiber Composites	
Respondent No.	**Knowledge Gains**
1	(1) creep performance of current carbon-fiber thermoplastic material, (2) overall durability test methods established in prior ORNL work is applicable to current material system
2	(1) test procedures and approaches for durability assessments of composites; (2) durability-based design criteria for automotive composites; (3) durability performance of a number of candidate matrix/fiber composites; (4) mechanics (behavior) of fiber-reinforced thermoset and thermoplastic matrix composites; (5) development of models for performance prediction of composites
3	significant information on processing and properties of PPS [phenylene sulfide] composites
4	(1) characterization of the long-term behavior of the carbon-fiber composite material in an automotive application to help identify areas of material deficiency and help designers optimize the composite components by providing property data; (2) test method development or modification for the specific family of composite materials; (3) development of testing machine control, data acquisition and analysis software that is useful in a wide variety of research programs; (4) development and distribution of testing methodology for evaluating candidate composite materials for automotive applications; (5) clear support for the use of composite materials in automotive applications (fatigue performance, temperature performance, impact behavior, etc.)
5	development of test methods and standards for discontinuous composites used in high-volume production industries and subjected to extreme automotive conditions

percent were not sure. Interests in collaboration were expressed on the following issues: materials; modeling behavior, testing, and durability assessment of fiber-reinforced composite materials; plastics, composites, nanotechnology; composites research of interest and beneficial to the ACC and others involved in similar research; automotive research; and additional research on thermoplastic composites and carbon-fiber manufacturing.

One researcher indicated that he did not see future research benefiting from this project, while another respondent was not sure. The remaining 63 percent could foresee other areas of research they might pursue in their careers that may benefit from this R&D effort.

Funding from DOE seems an incentive for this research effort for the private and/or public sector firms involved in this effort. Only one private sector researcher replied that he was "not sure" whether his company would have participated without DOE funding; the others responded that their organizations would *not* have engaged in research on durability. For those answering "why," funding and cost were cited as well as lack of internal staff, equipment, and knowledge base at organization.

Only 14 percent of those responding (N=1) felt that the results were sufficient for making carbon fibers a viable option for the auto industry; 71 percent indicated that they were not sure; 14 percent said no. When asked to identify barriers, of those providing reasons (N=7), all listed cost; four raised issues of manufacturing or processing of the carbon fibers; and two mentioned availability in large volumes. One respondent added identifying the appropriate fiber form to be compatible with available resin systems.

One participant felt that the program was well-run and that the research team at ORNL and UT provided the expertise needed to meet the objectives.

4.1.4 Low-cost carbon fibers from renewable resources

Researchers from ORNL, UT, MeadWestvaco, Eastman Chemical Company, and North Carolina State University were involved in the *low-cost carbon fibers from renewable resources* R&D project. The researcher at North Carolina State University passed away prior to this evaluation.

The majority of the respondents sensed that the objectives had been met—67 percent (N=6); one commented no, in that the project was still on-going, and one commented no, that preliminary work revealed technical challenges that were beyond the capability of the current resources devoted to the project. However, 100 percent of the researchers indicated that the research had revealed knowledge. A summary of what each participant felt were the key areas of knowledge gains are listed in Table 4.4. Although we did not encourage group responses, one team of researchers prepared a group response about lessons learned.

Table 4.4: Participants' Opinions on Knowledge Gains from R&D Effort—Low-Cost Carbon Fibers from Renewable Resources

Respondent No.	Knowledge Gains
1, 2, and 3	(1) industrial grade carbon fiber can be melt-extruded from blends containing > 75 percent lignin; (2) raw fiber can be extruded as multifilaments in a tow; (3) commercial lignin, thought to contain 3-10 percent contaminants, actually contains about 30 percent contaminants; (4) simple methods can be used to remove contaminants from lignin which improves spinning; (5) the proposed process appears to meet industrial economic goals; (6) if successfully transferred it would be valuable in (a) increasing forest products industry revenue and (b) decreasing imported oil, which is currently 27 percent of all U.S. energy
4	(1) how to make carbon fiber from new sources
5	(1) how to run a melt-spinning line driven by a twin-screw extruder; (2) find the temperature program for spinning lignin carbon fiber precursors; (3) find the spinning head configuration for spinning very thin lignin fibers at high spinning speeds; (4) find the carbonization parameters for lignin fibers' precursors; (5) find the lignin preparation procedure for spinning lignin carbon-fiber precursors
6	Technically, (1) the level of purity required for successful and economically viable conversion to carbon fiber; (2) the need for coformulants to manage the process, (3) the requirements for surface modification of the carbon fiber. Managerially, (1) the need for multidisciplinary research and more focused approach to both synthetic and materials-science aspects of the project; (2) need for better cooperation among the participants.

There had been *no* collaboration among the researchers with the organizations involved in this R&D effort prior to this project. One private-sector firm had worked with North Carolina State several years ago. ORNL had worked with *other* researchers at North Carolina State and UT from the late 1990s until the present time. There was uncertainty expressed by most respondents on whether there was a willingness to collaborate on future projects. Some respondents were concerned about propriety agreements, limitations on necessary equipment to conduct next project stage, and working relationships established in this effort. Other researchers indicated a willingness to collaborate with the other partners in the future. Research interest included enhancing the spinnability of lignin for carbon fiber precursors and efforts in lignin chemistry, polymer applications of natural products, and material applications of naturally occurring polymers.

Eighty-three percent of the respondents (N=5) could foresee other areas of research that might benefit from this R&D effort; only one respondent was not sure. The private-sector firms do not anticipate using the knowledge gained to develop a new product line. There was speculation that the building/construction industry could benefit from this R&D effort with an application towards structural reinforcement. The private-sector firm participating in the evaluation responded that his company had not used knowledge gained from this R&D to spin-off a new product.

The non-ORNL respondents would not have participated in this R&D effort without funding from DOE. Reasons cited include the uncertainty regarding commercialization and unacceptable risk levels for private sector involvement beyond low-level cooperative efforts.

When asked if the research efforts were sufficient to make carbon fibers a viable option for the automobile industry, 83 percent responded yes and 17 percent responded no. Regardless, most participants listed barriers to wide-scale introduction of low-cost carbon fibers in the manufacture of light-duty vehicles. High cost and low volume were mentioned, as was the fact that the cost of production of industrial carbon fiber from petroleum/petrochemicals is sensitive to the price of petroleum. Another respondent mentioned the absence of an adequate materials-science assessment of low-cost carbon fiber from naturally occurring materials.

We included an open-ended question for respondents to provide any additional comments. Some respondents felt that to achieve success, this R&D effort needs to be transferred to the private sector; some noted that the project facilitated collaboration with a national laboratory; and one researcher perceived the project as having the potential to significantly improve the energy consumption profile in the United States, as well as providing commercial outlets for materials from renewable resources. However, the researcher noted that more multidisciplinary work is needed before the risk level becomes manageable.

4.1.5 Low-cost carbon fiber development program

The project involved Hexcel Corporation and ORNL. All those participating in the project indicated that the technical objectives of the project were met and that the R&D project yielded knowledge. Knowledge gains are provided in Table 4.5. We expected and received some overlap in responses; however, participants who responded similarly to this question, did not respond similarly to other questions.

Table 4.5: Participants' Opinions on Knowledge Gains from R&D Effort— Low-Cost Carbon-Fiber Development Program	
Respondent No.	**Knowledge Gains**
1	(1) development of a new precursor for making carbon fiber; (2) development of a new process for carbonizing precursors; (3) development of a new process for oxidizing fibers; (4) development of a new method for surface treating fibers; (5) inspiring others to pursue research towards developing lower-cost carbon fiber
2 and 3	(1) technologies of low-cost carbon fiber; (2) polymer spinning technologies; (3) market economics; (4) polymer materials for carbon-fiber conversions; (5) stabilization and oxidation technologies
4	Low-cost carbon-fiber technologies via: (a) chemical modifications of textile PAN; (b) radiation treatment of textile PAN; (c) continuous sulfonation and carbonization of polyethylene fibers; (d) continuous sulfonation and carbonization of polypropylene fibers; (e) radiation treatment of melt-processable PAN
5	Low-cost carbon-fiber technologies—chemical modification of textile PAN, radiation treatment of textile PAN, state-of-the-art with respect to melt-processable PAN; economic analyses—quantification of the impact of raw material costs/carbon yields on final carbon-fiber costs; downstream processing—understanding the conversion processes needed to handle low-cost carbon-fiber forms
6	(1) ability to make reasonable tensile strength carbon fiber from textile acrylic PAN; (2) microwave processing to increase oxidation rate; (3) chemical treatment to increase oxidation rate; (4) methods for oxidation of polyolefin fibers; (5) status of world acrylic markets

The ORNL and Hexcel researchers had collaborated previously. Hexcel researchers had also collaborated with other researchers at ORNL in the late 1990s. In addition, Hexcel team members have collaborated with other national laboratories. These collaborations involved exchange of information and providing of material. Most of the collaboration involved carbon-fiber processing and recycling with application to the automotive sector.

All respondents indicated a willingness to collaborate in the future with ORNL on such issues as low-cost carbon fiber and development of composites for defense applications; carbon-fiber manufacturing technologies; applications of lightweighting materials for energy and automotive applications and other uses; developing new or alternative precursors and novel conversion techniques; development of carbon materials for industrial applications; carbon-fiber/nanotube and carbon nanotechnology-related research; development of next-generation high-performance carbon fibers. Hexcel respondents also expressed a willingness to collaborate with other national laboratories. In addition, all respondents could foresee other areas of research that they might pursue in their careers that could benefit from the results of this R&D project.

Hexcel respondents indicated that their firm would *not* have participated in R&D on low-cost carbon fibers without financial support from DOE. Reasons include risk, resources, and market demand. One participant pointed out that market conditions did not warrant investing internal R&D funds to develop high-risk technologies in spite of high payoff potential. Data on what research effort (person-years) it would have taken the company to achieve the same knowledge it now has by participating in the R&D effort are provided in section 4.4.6.

When asked if the private-sector firm would incorporate the results for the technology development for producing low-cost carbon fibers into product design for manufacturing parts for light-duty vehicles, 60 percent said no; 40 percent indicated that they were not sure. Lack of market demand and costs were cited by two respondents as reasons why it would not be incorporated. Two respondents mentioned that incorporation would require significant shifts in strategic business objectives, automotive industry acceptance for alternative raw materials, and market conditions towards substantially larger volume demands. Another participant indicated low market price for this fiber type, high capital costs to produce large quantities, and unknown market demand.

Hexcel has not used knowledge gained for spin-off of a new product. When asked of all participants if they were aware of any other firm or industrial sector that has benefited from this R&D effort, three replied yes: (1) the U.S. government in defense and aerospace; (2) acrylic textile manufacturers with application to carbon-fiber precursor development; and (3) acrylic textile manufacturers, polyolefin fiber manufacturers, and melt spinning service providers for application to carbon-fiber precursor development. The last respondent qualified the answer in terms of knowledge gained and shared.

Three of the respondents felt that the projected 22 percent cost reduction of carbon fibers resulting from this project was sufficient to make carbon fibers a viable option for the automobile industry. One respondent indicated that he was not sure, while another respondent said no. The last respondent indicated that the results were sufficient *if* results were coupled with other developments.

Despite the fact that this R&D effort focused on cost of carbon fibers, many participants felt that cost was still a barrier to widespread introduction of low-cost carbon fibers in the manufacture of light-duty vehicles. It was cited as one of the barriers by all six respondents. However, there were numerous additional barriers identified by the researchers: comfort with changing materials for crash-sensitive parts; market demand; uncertainties about sustainability of long-term and large-volume supply; performance of new, non-conventional materials in automotive products; lack of familiarity with processing technologies; inexpensive gasoline, customer conservatism, and lack of downstream conversion processes to deal with true low-cost product forms.

We included an open-ended question so that researchers could share additional thoughts on the R&D effort. Most researchers felt that the R&D effort was comprehensive in that it provided an opportunity to explore numerous technologies of potential value for low-cost carbon-fiber development. The assessment covered all aspects, including raw materials and methods and scale-up requirements. Economic analyses covered manufacturing processes, and the project allowed for discussions on marketing and technical issues with the automotive sector. Most felt the final report provided a comprehensive assessment of current activities in this field. In the end, however, many noted the uncertainty of quantifying future industrial demands.

4.1.6 Modeling of composite materials for energy absorption

The project involved researchers at Lawrence Livermore National Laboratory and ORNL. The respondents agreed that the technical objectives were met and that knowledge was generated. Table 4.6 presents knowledge gains.

Table 4.6: Participants' Opinions on Knowledge Gains from R&D Effort—Modeling of Composite Materials for Energy Absorption

Respondent No.	Knowledge Gains
1	(1) development of material-level models for crash; (2) development of a micro-mechanics model for composite crush; (3) development of a random fiber model as opposed to an engineered material model; (4) development of crush initiator triggers; (5) design of composite-intensive body structures
2	(1) determination of failure modes for discrete fiber composites; (2) rate dependency of the material; (3) material model for crash analysis that is based on simple characterization methods; (4) development of new test methods; (5) identification of localization behavior as the main area for further development

The research team members had *not* collaborated in the past, but indicated that they would be willing to collaborate in the future. Potential collaborations could focus on modeling and experimental efforts, modeling of material manufacturing and its effect on material performance, or development of new dynamic models for material characterization. The participants commented that they could foresee future career benefits resulting from this R&D effort.

The researchers were not sure of other industries besides the automobile sector that have benefited from this R&D effort, but this might be expected given the specificity of the technical objectives. One respondent felt that the shipbuilding industry might benefit in the future with application to boat hulls.

The two respondents disagreed as to whether the results of the project were sufficient to make carbon fibers a viable option to the automotive industry. The respondents cited as barriers to introduction of carbon fibers on a wide-scale basis (1) carbon-fiber cost and design platform comfort with changing materials, and (2) material uniformity, understanding of in-service behavior, predictive modeling of in-service behavior, and linking of manufacturing processing conditions to material properties. One respondent commented that the project's aim was to remove barriers to carbon-fiber composite introduction and was successful in removing the obstacle of material-level crash models.

4.1.7 Active flexible binder control system for robust stamping

This R&D effort involved the Big Three automakers and The Ohio State University. Nearly everyone—83 percent of participants—agreed that the objectives had been met. Nevertheless, all expressed the view that the project had yielded knowledge. Table 4.7 sets out those gains from the perspectives of those actively involved in the R&D project.

Table 4.7: Participants' Opinions on Knowledge Gains from R&D Effort— Active Flexible Binder Control System for Robust Stamping	
Respondent No.	**Knowledge Gains**
1	(1) binder can be controlled in real time with computer; (2) control can be consistent with computer; (3) control can be consistent even with differential material processes
2	(1) binder force can be controlled by computer during real-time stroke; (2) there can be consistent programmable binder-force control; (3) variable binder-force control provides opportunity to form different material panels without tooling changes; (4) multi-cell binder-force control provides quick forming condition changes for problem solving during tooling tryout
3	(1) flexible binders can work; (2) flexible binders are expensive; (3) best use may be in making prototypes; (4) simulation and intuition both can utilize flexible binders; (5) implementation will be difficult
4	(1) new forming technique; (2) metal-forming process control; (3) system concept of formability instead of material formability; (4) mind-set change is required to adopt the new technology; (5) more potential applications of the technology to form new materials such as magnesium
5	(1) software to program multiple-point cushions; (2) determination of material properties under biaxial state of stress; (3) capability to control hydraulic systems quickly; (4) potential increase capability in private sector
6	(1) building and designing flexible binders; (2) developing simulation/optimization capability for multi-point cushion systems; (3) building closed-loop system based on wrinkle-height measurements; (4) designing non-linear controller for multi-point cushion systems; (5) flexible binder technology reduces the time and lowers the cost for fine tuning stamping tools

Only two of the researchers involved in this project had previously collaborated; they worked together between 1996 and 2001 on a forming of aluminum project (see Das et al., 2001). Three of the six researchers had collaborated with other researchers at Ohio State or the Big Three. Eighty-three percent indicated a willingness to collaborate on future research, examining such general or specific issues as:

- how to implement results from this project
- variable binder-force application in stamping
- research that included a university/private sector partnership
- sheet-metal forming, forging, tribology
- research that involves automotive companies, material suppliers, and press shops

The majority of respondents (83%) could anticipate other areas of research that might benefit from this R&D effort.

With regard to the private sector using knowledge gained to spin-off a new product line, only 33 percent (N=2) expressed that his firm would use the knowledge gained. One researcher responded that his company was testing product applications during 2006 but did not have a projected year of commercialization. The second responded that transfer of R&D results would occur in 2006-07.

There was a belief that *other* firms or industries, not directly involved in *this* R&D project, could benefit from this project (N=5). Industries and/or firms mentioned specifically are presented in Table 4.8. Note that a firm or industrial sector may have been mentioned by more than one researcher, with different types of applications proffered. Only one participant felt that the metal-fabricating industry has *already* benefited from the R&D effort.

Table 4.8: Other Firms/Industrial Sectors That Could Benefit from Active Flexible Binder Control System for Robust Stamping

Firm/Industrial Sector	Type of Application
Aerospace industry	Stamping sheet-metal components
Appliance industry	Stamping sheet-metal components
Automotive suppliers	Stamping large sheet-metal parts
Stamping die manufacturers	Aluminum stamping die tryout with variable force control
Metal-fabricating industry	Sheet-metal forming using dies and stamping
Sheet-metal forming industry	Deep drawing
Transportation industry	Stamping sheet-metal components

Only one respondent indicated his firm would have participated in this R&D effort without funding from DOE. Although another participant said no, he pointed out that the company *may* have participated in partial aspects of the overall R&D effort, such as binder control for aluminum but not with the flexible binder system—the subject of this project. Reasons provided for not engaging in this research echo those cited elsewhere: lack of funding, high cost of research effort, lack of expertise.

When asked if the results of the research on *active flexible binder control system for robust stamping* were sufficient to make aluminum a viable option for the automobile industry, 67 percent responded yes (N=4). One researcher said no, another said "not sure."

However, there was less support on incorporating the results into the product design for light-duty vehicles: two researchers said yes but one with qualifications. One participant felt his company would be testing in a die tryout, with an uncertain projected year of commercialization. Another said the results would be used for high-strength steel stampings, with 2008 as the projected year of commercialization.

Leaving aside whether the results would be incorporated, most participants responded to an open-ended question on barriers to wide-scale introduction of lighter weight light-duty vehicles. The responses can be grouped into three themes: technical/engineering or manufacturing issues; cost; or other.

Barriers related to technical/engineering or manufacturing issues include

- sophisticated technology,
- specialized training,
- formability and dimensional quality (mentioned two times),
- lack of design for manufacturing concept (mentioned two times),
- parts geometry not designed for materials required by lighter weight vehicles, and
- understanding of manufacturability of new materials.

Costs included equipment and material costs. Another researcher felt the relative low cost of gasoline is a barrier to lighter weight vehicles. Finally, resistance to change was cited.

Additional comments were presented by a number of investigators. Two hoped to see the technology implemented in production. One researcher was concerned with the role of U.S. versus international companies' involvement in the R&D effort, specifically on the role of increasing U.S. firms' international competitiveness. Another felt the duration of projects should be shortened. A different respondent indicated that a technology-transfer program is required. Finally, an investigator echoed that due to the technical/engineering or manufacturing issues identified as barriers, the technology will not implemented in the near future.

4.1.8 Lightweighting front structures

This R&D effort involved the Big Three automakers, U.S. Steel, and the Auto/Steel Partnership. All researchers agreed that the objectives had been met and that knowledge was gained through the research effort. Table 4.9 describes those gains.

Table 4.9: Participants' Opinions on Knowledge Gains from R&D Effort—Lightweighting Front Structures

Respondent No.	Knowledge Gains
1	(1) advanced high-strength steel (AHSS) design achieved a mass reduction of 22.4% compared to baseline; (2) performance was the same as baseline; (3) AHSS design was validated by conducting a successful NCAP 35 mph rigid barrier impact test; (4) can be concluded that use of AHSS in conjunction with effective part design can result in significant mass reduction in crash-sensitive applications; (5) parts can be made from Dual Phase (DP) 800and DP 980 steels when attention is given to manufacturing constraints early in design
2	(1) application of AHSS can save mass in vehicle-form rail systems and maintain crash performance; (2) materials can be resistance spot welded to each other and welds can resist loads experienced during crash event; (3) complex part geometries can be stamped from DP 780T and DP 980T material; (4) DP 780T material can be laser welded together to make tailor-welded blanks; (5) AHSS can be MIG welded together to perform an effective repair of rail system
3	AHSS can save over 20% mass over high-strength steel (HSS) with proper design; (2) AHSS solutions can be incorporated into existing package space of real-world designs; (3) AHSS solutions can save 20% mass over HSS at no additional cost; (4) AHSS solutions are suitable for high-volume manufacturing within existing manufacturing infrastructure; (5) computer optimization algorithms for structural application can yield non-intuitive mass savings

Two of the researchers involved in this project had *not* previously collaborated; only one had collaborated with others working on this project. While two of the researchers had not worked with those on this project, they had worked with other persons in the organizations involved in this R&D effort. All expressed an interest in collaborating on future research efforts on such issues as lightweighting steel designs. Two-thirds of the respondents could anticipate other areas of research that might benefit from this R&D effort.

With regard to the private sector using knowledge gained to spin-off a new product line, only 33 percent (N=1) expressed that the firm would use the knowledge gained. The researcher said his company would use the Lambda platform with commercialization in 2006. One researcher responded affirmatively to our inquiry on whether the results of the R&D project on use of advanced high-strength steel for *lightweighting front structures* would be incorporated by the company into product design for light-duty vehicles. Product applications were Lambda, with anticipated commercialization date of 2006; Epsilon, 2008; and Delta, 2010.

One investigator felt that any industry interested in affordable mass reduction or performance improvements *could* benefit from this R&D effort.

Two respondents indicated their firms would have participated in this R&D effort without funding from DOE. When asked if the results of the research on use of AHSS for *lightweighting front structures* were sufficient to make AHSS a viable option for the automobile industry, 67 percent responded yes.

In response to an open-ended question on barriers to wide-scale introduction of lighter weight vehicles, barriers cited were parts fabrication, joining technologies, and, in a broader perspective, the infrastructure needed to support an industrial production of 17 million units per year. The investment required is not only of the automakers but their suppliers. The steel industry would need to increase production, requiring capital investments, but confidence in the growth is needed. Another barrier raised was quality standards.

4.1.9 Magnesium powertrain cast components

The project team for the *magnesium powertrain cast components* R&D project included the Big Three automakers; alloys, casting houses, and recycling, tooling, testing, and modeling companies; academia; and Natural Resources Canada. Through discussions among the project administrator, principal investigator, technical field manager, and research team, it was decided to seek input from 41 key researchers, representing 34 organizations. This decision reflected our intent to gather information from those making significant contributions to the effort.

Slightly over half of the respondents—55 percent (N=16) —thought that the objectives had been met. Thirty-one percent (N=9) expressed uncertainty (i.e., were “not sure”), but each qualified his/her response. The majority of the qualifications, as displayed in Table 4.10, reflect a researcher’s inability to comment on the project’s overall objectives, as opposed to specific objectives for his or her task.

Three of the participants responded “no” when asked if the objectives had been met, but they qualified their responses. Their remarks were (1) the main project—development of magnesium-intensive engine (engine block, oil pan, front cover)—is currently being completed with scheduled testing tentatively set to start in September 2006; five associated research projects are just underway and may not be completed until late 2007; (2) demonstration of feasibility remains

Table 4.10: Reasons Objectives Not Met Magnesium Powertrain Cast Components R&D Effort	
Respondent No.	**Qualification on Why Objectives Not Met**
1	Data was generated for the material properties but feasible use of the materials selected was not successful
2	I have only been involved with a part of the project. It is not always clear what is being done in other areas. Although we are behind on timing, it looks like most objectives are being met in the area we are involved.
3	We are only involved in the project on a very limited basis
4	I assume the objective was to save weight using magnesium instead of aluminum in an engine. Since the engine has yet to be made or tested, it is difficult to say whether the objective has been met.
5	The program has not reached its conclusion.
6	On-going research. Results vary from completed to not started.
7	The program is still in progress and has only partially been completed, although many of the target objectives have been achieved (e.g., design, alloy development, test castings, corrosion measurements, etc.).
8	While the ongoing milestones are being met, the final deliverable—whether the designed magnesium-intensive engine survives the engine dynamometer testing—is yet to be accomplished;. There are actually five R&D projects within the Magnesium Powertrain Cast Components project. Good progress is being made on each of these.
9	The research objectives of our projects are being met. However, this question addresses a broader issue of which I have no knowledge.

to be seen in a successful dynamometer test of the engine with magnesium powertrain cast components, and a solution to the recyclability issues of newly developed creep-resistant magnesium alloys; and (3) the work is still in progress—several objectives have been met to date and most will be met by the end of the project.

Ninety percent (N=26) of the investigators indicated that the research had revealed knowledge. A summary of respondents' (N=24) perceptions of the key areas of knowledge gains is listed in Table 4.11.

Table 4.11: Participants' Opinions on Knowledge Gains from R&D Effort—Magnesium Powertrain Cast Components	
Respondent No.	**Knowledge Gains**
1	(1) material property data on different newly developed magnesium alloys; (2) die-castability evaluation of new magnesium alloys; (3) magnesium powertrain component design; (4) magnesium corrosion performance understanding; (5) engine coolant development
2	(1) physical property tables of the materials selected; (2) some knowledge of the issues with casting the selected materials; (3) new process will need to be found to process these new alloys
3	(1) independent property data on new alloys; (2) specific and quantifiable corrosion data; (3) alloy to application matching; (4) design techniques
4	(1) additional weight savings compared with aluminum can be achieved with MRI153m and MRI230D magnesium alloys; (2) castability of complex shapes; (3) user-friendliness of those alloys; (4) process-parameters development adapted to these new alloys; (5) corrosion resistance as good as aluminum
5	(1) there are a large number of potential alloys that could be used in auto manufacture; (2) corrosion of magnesium can be controlled and may not be as big an issue as thought; (3) more time and effort should be used in designing components to be better suited to HPDC process
6	(1) results are not measured in patents or publications, but rather in the acceptance this work fostered in the OEMs. Based to a great extent on this work, all three OEMs are now using or specifying use of a particular resonant-testing method for production products; (2) knowledge gained in this USCAR project encouraged change. The changes are permitting better risk reduction and lower cost; (3) there is potential for weight and cost reduction in the application of this project. The results have exceeded expectations
7	(1) castability of material of choice needs to be better defined due to issues in thermal constraints and sink spots relating to those issues; (2) defects are in the area of thick and thin sections producing shrink cracks
8	(1) castability; (2) mechanical properties; (3) corrosion
9	(1) identification of coolants that work with magnesium; (2) new methods to study microstructure; (3) criteria for selection of an alloy; (4) die-casting and sand-casting characteristics of alloys studies; (5) database of alloy properties
10	(1) development of magnesium-alloy material-property database from metallurgical testing; (2) development of creep-resistant magnesium alloys; (3) research into recycling of new magnesium alloys
11	(1) mechanical properties; (2) creep issues with magnesium; (3) improved understanding of alloy properties; (4) lubrication materials; (5) cooperative effort to a common goal
12	(1) material-property database; (2) low-pressure magnesium casting process development; (3) engine-block design; (4) alloy development; (5) thermal spray cylinder development
13	(1) mechanical properties of the high-temperature alloys (not just supplier data); (2) casting behavior of alloys in real components (not just plates); (3) corrosion issues with coolants and galvanic issues with gaskets; (4) block-durability capability of these alloys; (5) design considerations for specific types of components for these alloys
14	(1) material-property database developed on several die cast and sand cast magnesium creep resistant alloys; (2) die casting process parameters on magnesium creep resistant alloys; (3) sand casting parameters; (4) engine block design; (5) engine block FEA

Table 4.11: continued	
15	(1) design methodology for novel creep-resisting magnesium alloys; (2) corrosion behavior of novel creep-resisting magnesium alloys; (3) practical foundry experience with novel magnesium alloys; (4) extensive mechanical property database for novel magnesium alloys; (5) identification of need for recycling infrastructure for these new materials
16	(1) alloy evaluation; (2) structural design changes required for magnesium block; (3) engine coolant required for magnesium blocks; (4) the part of the project where my expertise lies is just starting.
17	(1) worldwide high-temperature-creep magnesium alloys baseline study with subsequent castability study and alloy downselect trade-off study using pair-wise comparison format; (2) lightweighting materials property database; (3) magnesium block design; (4) FEA analysis validation of magnesium block, SOP, FEC, ROSC subsystem; (5) cast magnesium-intensive engine validation (on-going)
18	(1) possible to design on paper a magnesium-intensive engine using magnesium alloys that are commercially viable, commercially available today; (2) corrosion of magnesium can be addressed in the engine design. It is technically feasible, although expensive, to control magnesium corrosion; (3) target of 15% mass reduction for cast components of magnesium-intensive engine was actually low; (4) high thermal expansion coefficient of magnesium (relative to aluminum and steel) would be largest design challenge; (5) that GM, Ford, and DaimlerChrysler, and over 40 other organizations, could work together effectively to accomplish the deliverables of project
19	(1) lightweighting materials property database (information from actual parts); (2) baseline comparison of attributes of commercially available creep-resistant magnesium alloys; (3) analytically demonstrated feasibility of producing primary engine components in magnesium
20	(1) there is a global interest in and need for many deliverables being pursued; (2) commercial interests cannot be divorced from technical enablers; (3) because of this project, current array of emerging low-cost, high-temperature, creep-resistant magnesium alloys are at the threshold of proving potential for wide-spread use in demanding structural applications; (4) more development is needed to ensure alloy availability, refined product design knowledge, and correspondingly refined cost structures, globally-competitive manufacturing practices, and optimum environmental friendliness throughout the product lifecycle; (5) corrosion remains a fundamental challenge for alloy developers, product component and system designers, engineers and specifiers, manufacturers, and users.
21	(1) determination of thermochemical properties of several magnesium-containing alloy systems through first-principles calculations; (2) development of thermodynamically consistent thermodynamic databases; (3) identification of critical experiments that need to be performed in order to gain a better understanding of the phase equilibria in selected systems; (4) effects of alloying on creep resistance of magnesium-alloys have been elucidated; (5) identification of promising creep-resistant magnesium alloys through an integrated approach
22	(1) corrosion rates of experimental magnesium alloys; (2) electrochemical test method protocol; (3) titration method; (4) hydrogen evolution method; (5) RBS data
23 and 24*	(1) solving technical barriers to increase the market share of magnesium in the auto sector; (2) design constraints to be taken into account while changing from aluminum to magnesium without sacrificing quality or performance; (3) fundamental understanding of the physical metallurgy of magnesium alloys; (4) teamwork, collaboration among the auto industry, ingot producers, universities, and research organizations; (5) data on properties of new high-temperature magnesium alloys
* As noted elsewhere in this report, group responses were not encouraged. On the other hand, it was reasonable that persons from the organization would collaborate on questions.	

Half of the researchers had previously collaborated with colleagues on this project.[31] To some extent, a new research team was assembled for the current effort. Of those who had collaborated in the past, the projects varied, as did the timing of them (from 1994 to current). Among those who listed projects from past collaboration,[32]

- one had participated in a rapid tooling project (see Das et al., 2002),
- two had collaborated on cost reductions for magnesium castings (CORMAG),
- three had worked on casting projects
- one on corrosion,
- one on aluminum chassis and magnesium cradle,
- two on engine cradles, and
- one on hybrid prototypes.

Moreover, less than half of the investigators had worked with other researchers from the organizations involved in this project. Only 46 percent (N=13) had worked together in the past. Collaborations with other researchers at organizations involved in this R&D effort included: alloys development, demonstration projects, thermal spray, castings, hybrid prototype, and proprietary research.

An overwhelming majority of the participants—93 percent (N=26)—expressed a willingness to collaborate with the other partners involved in this R&D effort:. More than 35 projects were identified. Here they have been grouped by broad category, with number of references to this research:

- casting (7)
- alloy development (7)
- magnesium applications (5)
- mechanical testing/evaluations (2)
- thermophysical properties/thermodynamics (2)
- cylinder (2)
- creep resistance (2)
- alloy recycling (2)
- technology transfer to Tier one suppliers (1)
- development of diesel dosing system (1)

Sixty-nine percent of the respondents (N=18) could foresee other areas of research that might benefit from this R&D effort.

With regard to the private sector using knowledge gained to spin-off a new product line, researchers representing five companies responded. Researchers from one firm have used the knowledge for a torque-converter stator with commercialization in 2006, and one respondent indicated that knowledge will be used for an oil pan, although the commercialization date is not known at this point. Another company had used the knowledge for suspension knuckles and control arms (commercialization in 2004 and 2005), cylinder heads (2005); and cylinder heads and blocks (2006); diecast version of alloy commercialized in 2006. Another researcher

[31] One investigator did not respond to this question.
[32] The research results on one collaboration were cited as proprietary.

mentioned the Corvette Z'06, model year 2006, while another investigator with that firm mentioned powertrain components with a projected commercialization timeframe of 2008-09.

There was an assertion that *other* firms or industries, not directly involved in this R&D, could benefit from this project (N=18). One respondent repeated that the Big Three could benefit with automotive applications. Other industries mentioned specifically are presented in Table 4.12. Note that an industrial sector may have been mentioned by more than one researcher, with different types of applications proffered.

Table 4.12: Other Firms/Industrial Sectors That Could Benefit from Magnesium Powertrain Cast Components

Firm/Industrial Sector	Type of Application
Aerospace	Testing blades, vanes, shafts, bearings and rotors Testing new and in-service parts
Casting industry	Automotive and marine applications Creep-resistant magnesium components Powertrain components Safety critical components
Ceramic	Catalytic carrier cores Oxygen sensors
Engine coolant	Magnesium-compatible engine coolants
Equipment manufacturers generally	Lightweighting
European and Asian automakers	Engine Powertrain components
Magnesium alloy ingot producers	Wide range of automotive applications High temperature applications
Metal finishing	Coatings and surface treatments for magnesium
Motorcycle manufacturers	Powertrain
Parts manufacturers	Automotive components such as engine blocks
Portable generator manufacturers	Engines
Small engine manufacturers	Engines
Snowmobile and all terrain vehicle manufacturers	Small engines and transmissions
U.S. Department of Defense	Lightweighting powertrains Military hardware
Universities	Alloy research

With regard to other firms or industrial sectors that *have* benefited from the results of this effort, participants mentioned

- magnesium and magnesium-alloy producers (three respondents),
- design and computer-aided engineering sector; tooling; materials testing firms, and those engaged in fasteners, gaskets, coolants, coating, and sealing, and
- the metal-casting sector (two respondents).

With regard to whether the firms would have participated in this R&D effort without funding from DOE,

- 9 responded yes;
- 3, no;
- 4, not sure;
- 5, no with comments; and
- 7, not sure with comments.[33]

The comments accompanying a “no” or “not sure” response could be grouped into resource allocation (too costly, limited resources availability, uncertainty on commitment); business practices (would evaluate whether R&D effort would be profitable for firm); or limited-scale R&D (not as extensive).

When asked if the research efforts were sufficient to make magnesium a viable option for the automobile industry, 55 percent responded yes; 21 percent, no; and 24 percent, not sure.[34]

In response to whether the results of the R&D project would be incorporated by a company into the product design for light-duty vehicles, nine said not sure; eight said no, and eight said yes. The applications and projected commercialization data are presented in Table 4.13.

Table 4.13: Application and Commercialization Date Results of Magnesium Powertrain Cast Components Incorporated into Product Design

Respondent No.	Application	Commercialization Date
1	Oil pans	To be determined
2	Powertrain, safety critical parts	2006 and beyond
3	Front covers	2008
4	Fasteners	To be determined
5	Transmissions	To be determined
6 and 7	Powertrain components (valve covers, front covers, oil pans, transmission components, transfer cases)	Over next 5 years
8	To be determined	To be determined

Leaving aside whether the results would be incorporated, 26 participants mentioned more than 70 barriers to wide-scale introduction. We grouped the barriers into categories, as presented below. Numbers in parentheses note the number of times the barrier was referred to:

- cost (22),
- manufacturing issues (8),
- corrosion (8),
- recyclability (3),
- OEM reluctance (6),
- magnesium alloy infrastructure (7),
- lack of design knowledge/experience (8),

[33] There was one non-response.

[34] One investigator added that standing alone the results are not sufficient to make magnesium a viable option; however, he added that it would contribute significantly to making magnesium more visible.

- international tariff policies (3),
- safety (3),[35]
- creeping (2),
- competing technologies/materials (2), and
- other (4).

The last portion of our qualitative evaluation allows the key researchers to provide comments. In this case, seven responded. One commented that DOE co-funding afforded an opportunity to attract major participants in the project. There were several remarks about competing organizations working openly and effectively. This collaborative environment was noted several times. One respondent noted that the research created opportunities for small companies to work on a large R&D effort.

However, a few respondents (of the 24) expressed frustration toward the OEMs. Researchers felt that senior managers did not have an interest in the project or results; benefits were ignored by some in the OEM technical community. There was an interest in information emanating from the project being diffused to all levels of the Big Three automakers, and time for USCAR to guide implementation.

4.1.10 Structural cast magnesium development

The project team for the *structural cast magnesium development* (SCMD) R&D project included the Big Three automakers, companies from the casting supply base, academia, independent testing and research laboratories, the American Foundry Society, technical associations, three national laboratories (Oak Ridge, Sandia, and Lawrence Livermore), and Natural Resources Canada. Through discussions among the project administrator, principal investigator, technical field manager, and research team, it was decided to seek input from 29 key researchers, representing 23 organizations. This was based on our intent to gather information from those making significant contributions to the SCMD effort. One person left the organization a few weeks before the data collection endeavor was undertaken, leaving 28 researchers to participant; 20 responded.

The majority of the respondents—90 percent (N=18)—thought that the objectives had been met. The remaining 10 percent (N=2) who responded expressed the feeling that insufficient funds were allocated to address low pressure permanent molding. However, 100 percent of the researchers indicated that the research had produced knowledge. A summary of respondents' assessments of key areas of knowledge gains is included as Table 4.14.

[35] Concern over burning.

Table 4.14: Participants' Opinions on Knowledge Gains from R&D Effort—Structural Cast Magnesium Development	
Respondent No.	**Knowledge Gains**
1	(1) magnesium corrosion mechanisms and the potential for developing cost-effective and environment-friendly method for protection from galvanic corrosion; (2) magnesium fatigue mechanisms; (3) relationships between processing-microstructure-behavior; (4) casting simulation; (5) effects of temperature, dwell time, and cyclic loading on magnesium behavior and their impact on bolt-load-retention, reliability, durability, and design
2	(1) much better definition of the properties of the magnesium alloys; (2) the resistance to corrosion of magnesium is much better than generally thought; (3) optimization of a design is much more involved than what there is generally allotted time-wise with production parts; (4) the industry does not utilize the known and published process engineering formulas and data; (5) magnesium does not save as much weight as generally believed since the parts being replaced were not optimized for their material
3	(1) materials properties; (2) development of high-temperature magnesium alloy; (3) improved understanding of corrosion; (4) improved NDE methods
4	(1) for magnesium die casting, the amount and location of the trapped air are directly correlated with casting defects; (2) segregation is important in magnesium HPDC
5	(1) casting processing technologies, (2) casting alloys and properties; (3) surface protections, (4) joining with dissimilar materials; (5) vehicle validation testing
6	(1) magnesium automotive components can be used and function well in harsh environments; (2) magnesium alloy design properties and functional database; (3) galvanic-corrosion mitigation solutions; (4) creep behavior of magnesium alloys and how to accomplish bolt-load retention on highly stressed joints; (5) improved high-velocity mold-fill simulation modeling capability that was used to improve cast component quality; (6) characterization of magnesium alloy microstructures; (7) X-ray evaluation techniques and improved quality indicators
7	(1) proper choice of a magnesium alloy to solve a specific problem—called "creep"; (2) the need to protect against corrosion; (3) the importance of choosing the right fasteners; (4) the fact that coating a part can sometimes cause more problems than non-coating; (5) the magnesium industry has been dormant since World War Two—and this project has indicated the applications of magnesium to a very severe application of a vehicle will be acceptable
8	(1) magnesium can successfully be used in place of aluminum for demanding structural exterior applications; (2) design for the manufacturing process must be done early in the design/re-design process; (3) extensive characterization of various magnesium alloys (microstructure, castability, creep performance, and other mechanical properties); (4) X-ray inspection/ranking does not necessarily correlate to product performance; (5) corrosion performance can be matched to aluminum alloy requirements through design and isolation
9	(1) casting process optimization for a production part; (2) database of material properties; (3) modeling of failure mechanisms
10	(1) magnesium material properties obtained and assembled in user-friendly database; (2) fabrication techniques demonstrated for physical radiographic reference are far superior to present ASTM radiographic reference films; (3) modeling algorithms for magnesium components

11	(1) identified that gate-flow and lubricant-application effects were not well known; (2) new data-acquisition method developed and tested for commercial lubricants to obtain data on cooling effects during lubricant application; (3) degradation properties of lubricant obtained from experiments; (4) data acquisition developed and tested on aluminum alloys for obtaining data on heat-flux and heat-transfer coefficients at metal-mold interfaces; (5) particle size and break up investigated using experiments with warm water as analogue material to magnesium alloys
12	(1) unified approach to model fatigue/failure/corrosion in magnesium alloys; (2) database for mechanical properties of magnesium alloys; (3) identification of research needs for widespread application of magnesium alloys in automotive industry; (4) specific research areas to be addressed to improve predictions on mechanical response of magnesium alloys
13	(1) knowledge of high-performance alloys for high-temperature creep resistance; (2) knowledge of extent of galvanic corrosion and corrosion prevention strategies; (3) computational capability for mold filling and solidification of magnesium in complex high-pressure die casting; (4) appropriate test procedures for bolt-load retention, and relative impact of tension-compression anisotropy for the automotive application; (5) technology roadmap (Magnesium 2020 report) for magnesium use in automotive applications
14	(1) structural parts could be made using high-pressure die casting (HPDC) and from magnesium that would satisfy rigorous automotive certification; (2) large, readily available database of magnesium mechanical properties was collected from actual samples rather than test bar which will allow designs to design magnesium castings using the lightest weight (thinnest walls, lowest cost) and the best function so that magnesium can be more competitive with other materials; (3) automotive company performed rigorous testing and demonstrated that magnesium castings can be lower in cost than competitive materials and provide useful functional advantage; (4) non-destructive testing capability was developed for X-ray certification that can be used to quantify potential defects via digital characteristics rather than analog and potentially error-prone operations; (5) microscopy developments showed three dimensional reconstruction of solidification structures (defects, dendrites, grains, inclusions) allowing quantitative measurement that can be related to process and component design; (6) Magnesium 2020 report can define North American strategy for global magnesium R&D and technological innovation
15	(1) die-casting process development; (2) new materials applications; (3) low-pressure casting “know how”; (4) use of ultra-light-weight magnesium in non-traditional applications; (5) simulation of new alloys
16	(1) quantitative processing-microstructure-property relationships in HPDC; (2) discovery of inverse surface segregation in HPDC magnesium alloys and its effects on fatigue properties; (3) development of new image-analysis technique to automatically segment gas and shrinkage pores and to quantify them in the HPDC magnesium-alloy microstructures; (4) development of magnesium microstructure properties database; (5) reconstruction of 3-dimensional HPDC magnesium-alloy microstructures and their utility in modeling mechanical response of the cast magnesium-alloy components
17	(1) die-cast magnesium casting may be used in structural automotive applications; (2) magnesium castings may be successfully cast in low-pressure casting processes; (3) magnesium castings cannot be used with traditional aluminum casting mold coatings; (4) mold coatings can be successfully modified to work with magnesium castings
18	(1) Better understanding of (a) magnesium HPDC processes; (b) magnesium microstructure and its effects on material properties of several magnesium alloys; (c) corrosion effects on magnesium; (2) comprehensive magnesium material property database; (3) development of a microstructure-property material model for finite element analysis modeling

The majority of the researchers involved in the SCMD R&D effort had collaborated in the past – on the cast light metals R&D project undertaken in the late 1990s and early 2000s (see Das et al., 2002, for an evaluation of that project). In fact, only 3 of the 20 researchers had not collaborated with the other *researchers* engaged in this effort and only 6 of the 20 respondents had not collaborated with the other *institutions* involved in this effort prior to this project. All of the participants expressed a willingness to collaborate on additional undertakings. Future research interests cited fell into two groups: interest in further collaborations with the organizations involved here (nine contributors remarked on this) or specific engineering/design topics (eight respondents). Researchers providing specific topics mentioned

- development and refinement of existing equations for confirmation of coefficients in process and mold design for pressure die castings,
- alloys development applied to specific powertrain application,
- optimization of magnesium low-pressure castings in permanent molds and sand molds,
- computer castings, solidification modeling, and total component failure evaluation analysis of individual components to full-size vehicles,
- corrosion, fastening, improvement of overall HPDC manufacturing capacity, reduction of development costs and time for producing prototypes, enhancing existing HPDC process to create high-integrity magnesium casting,
- applied materials development and system solutions for lightweighting vehicles,
- development of advanced automotive materials, production processes, and evaluation and screening methods, and
- multi-scale material modeling approaches.

Seventy-five percent (N=15) of the respondents could foresee other areas of research that might benefit from this R&D effort. Three participants representing the private sector and universities involved in this undertaking felt the overall knowledge gained could be used for future research or training students. One researcher felt that all participants could benefit from the knowledge gained.

With regard to the private sector using knowledge gained to spin-off a new product line, one respondent indicated that the magnesium front-engine crossmember was commercialized in 2005 and is being used in production at the firm. Another private-sector firm responded that the knowledge gained will be used in coatings for washers, with commercialization anticipated for 2009.

There was an assertion that other firms or industries, not directly involved in this R&D, could benefit from this project (N=11). Industries and/or firms mentioned specifically are presented in Table 4.15. Note that a firm or industrial sector may have been mentioned by more than one researcher, with different types of applications proffered.

Table 4.15: Other Firms/Industrial Sectors That Could Benefit from Structural Cast Magnesium Development	
Firm/Industrial Sector	**Type of Application**
Aerospace	Low-pressure data structural components (e.g., seats, overhead compartments)
Automotive foundries	cradles, control arms
Automotive	structural components chassis and other tough service application parts
Computer	frames
Defense	lightweighting transportation vehicles
Hand-held equipment	structural cases and covers for motors
National laboratories	multi-scale material modeling
Magnesium die-casting industry	sale of cast components
Magnesium	sale of primary magnesium
Quality testing/nondestructive evaluation/inspection	improved radiographic reference standards for inspection of magnesium, aluminum, steel castings
Sporting goods	bows, tennis racquets
Telecommunication	cell phone frames
Transportation	lightweighting mass transit vehicle structural components, seats, etc. lightweighting motorcycles, buses, bicycles, planes, trains

With regard to other firms or industrial sectors that *have* benefited from the results of this effort,

- two respondents named two firms as having gained an understanding of a particular aspect of working with magnesium,
- three *re-emphasized* the Big Three (with regard to knowledge and application on the front engine cradle),
- one referenced the broader modeling community with improved modeling techniques for magnesium alloys,
- one pointed out universities are refining their technical capabilities, and
- one cited the magnesium supplier industry with visibility, alloys, applications, process improvements.

Three of the respondents indicated their firm would have participated in this R&D effort without funding from DOE.[36] However, one of the three indicated that the participation would not have been to the same extent as with federal funding. Two respondents did not know if their company would have taken part in research covered under this project.

Ten respondents believed their companies or institutions would *not* have participated without federal funding, citing reasons such as:

- too many resources required (person hours, financial, and/or unwillingness of firm to finance "major" development project),

[36] The question of participating without DOE funding was *not* posed to the three national laboratories involved in this project.

- federal presence needed to (a) facilitate pre-competitive research, (b) alleviate potentially adversarial role between the Big Three and supply chain and to enhance synergy between suppliers and Big Three; (c) explore use of magnesium in a large structural component,
- firm did not currently work with magnesium alloys, and
- universities were not allocated funding for magnesium research.

When asked if the research efforts were sufficient to make magnesium a viable option for the automobile industry, 58 percent responded yes; 32 percent, no; and 11 percent, not sure. Two researchers who answered “no” (1) felt that more work was needed and (2) that the project by itself was insufficient to make magnesium an option but noted that the project demonstrated a step forward in the use of magnesium. One of the participants who expressed a “not sure” felt that more projects like this were needed to reveal the capabilities of magnesium to the OEMs.

With regard to whether the results of the R&D project would be incorporated by a company into the product design for light-duty vehicles, eight researchers said yes. Two noted that General Motors’ has used the results for the engine cradle in its model year 2006 Corvette Z’06. One firm will use the results in 2006 for coatings for washers. Another respondent indicated that the magnesium database produced from the project has been incorporated to the firm’s database, and also indicated that the firm hopes to introduce magnesium into the front vehicle structure of an automobile by 2014. Although several thought the results would be incorporated, they could not list specific product application or year of commercialization. They instead felt that the diffusion of information generated from the project would facilitate penetration of magnesium into the product design for light-duty vehicles.

Apart from whether the results would be incorporated, most participants responded to an open-ended question on barriers to wide-scale introduction of magnesium in the manufacture of light-duty vehicles. In fact, the respondents were quite expressive on barriers to introduction (19 out of 20 respondents listed at least one barrier, several offered more than one). We grouped the barriers into these themes, with number of times barrier was mentioned:

- engineering community acceptance/knowledge/leadership to embrace magnesium (8),
- material performance in general or specifically with regard to corrosion (6),
- cost of magnesium (6),
- regulatory constraints, e.g., tariffs (2),
- market supply/manufacturing infrastructure (3),
- alternative lightweighting materials (1), and
- unresolved research issues (7).[37]

Thirteen investigators provided additional comments. With a project this large in terms of participants, areas investigated, and financial resources expanded, negative comments should be expected and they were received. However, they were a minority of views expressed.
One respondent thought the funding was inadequate and questioned USCAR’s decision-making. Another felt that the R&D lacked depth in exploring equations and coefficients, and finally one participant felt that several organizations did not perform to expected levels.

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[37] These include: die cast application, general large scale R&D effort, modeling, R&D to over known remaining technical issues.

On the other hand, there were several positive comments. Managers felt the research improved communication and knowledge transfer among suppliers, OEMs, and research organizations (laboratories, universities). Networking was facilitated, and open communication among team members on challenges to incorporation of magnesium was made possible. One contributor felt the correct amount of resources were allocated and was complimentary of the project management's coordination effort. Another heralded the successful use of magnesium in the Corvette. Some noted that the project was beneficial to the U.S. auto industry and DOE and will advance the use of magnesium that in turn will reduce fuel consumption. Additional observations were that the project was necessary because it resulted in shared risk among the Big Three automakers and is important if the United States is to lead in research and commercial application of magnesium. One researcher felt DOE should keep the team together to explore other lightweighting materials.

There was a sense of "unfinished business" that was prevalent in the open-ended comments, however. These were expressed through such comments as need to share what was learned, next step is to promote within the OEMs, implementation is now necessary, and "demonstration" occurred. One contributor recommended a joint partnership with China since the country produces large amounts of magnesium and has an interest in fuel economy. One participant was uncertain on whether the demonstration met USCAR's requirement for pre-competitive auto components.

4.1.11 Summary of qualitative assessment

Table 4.16 summarizes the qualitative assessments for the nine projects. The non-composites section of the table includes respondents' opinions about whether their project's results would be incorporated into product design for light-duty vehicles. This question was primarily for the Big Three automakers and their suppliers. It was not posed to national laboratories and not applicable to universities and technical societies that might be engaged in the research effort.

Overall, the results are positive in each set. There was 100-percent agreement that technical objectives were met in two of the five of the projects—*low-cost carbon-fiber development* project and *modeling composite materials for energy absorption*. Although there was not unanimous agreement in the remaining three composite projects, there were qualifiers on two projects: composite-intensive body structure for *focal project 3* and *low-cost carbon fibers from renewable resources*. Respondents pointed out that the *composite-intensive body structure project* was on-going at the time of data collection and it was, thus, premature to say that the objectives were met. Other respondents were involved in only one task and did not wish to speak for the overall project. A similar reaction that the project was still on-going was found in the *low-cost carbon fibers from renewable resources* project, although 17 percent indicated no because technical challenges were revealed that need to be addressed. Finally, 88 percent of the

Table 4.16: Summary of Qualitative Assessments						
Project	**Met technical objectives?**	**Yielded knowledge?**	**Participated without DOE funding?[(1)]**	**Was collaboration enhanced?[(2)]**	**Will results be incorporated into product design for light-duty vehicles?[(3)]**	**Results sufficient for material to be a viable option?**
Carbon-fiber Composites						
Composite-intensive body structure for focal project 3	Yes (50%, N=3) [(4)]	Yes (100%, N=6)	Yes (16%, N=1)	Yes (100%, N=6)	na[(5)]	Yes (33%, N=2)
Durability of carbon-fiber composites	Yes (88%, N=7)	Yes (88%, N=7)	Yes (33%, N=1)	Yes (86%, N=6)	na	Yes (14%, N=1)
Low-cost carbon fibers from renewable resources	Yes (67%, N=4)	Yes (100%, N=6)	Yes (0%, N=0)	Yes (50%, N=3)	na	Yes (83%, N=5)
Low-cost carbon-fiber development program	Yes (100%, N=6)	Yes (100%, N=6)	Yes (0%, N=0)	Yes (100%, N=6)	na	Yes (67%, N=4)
Modeling of composite materials for energy absorption	Yes (100%, N=2)	Yes (100%, N=2)	N/A[(1)]	Yes (100%, N=2)	na	Yes (50%, N=1)
Non-Composite Lightweighting Materials Projects						
Active flexible binder control system for robust stamping	Yes (83%, N=5)	Yes (100%, N=6)	Yes (17%, N=1)	Yes (83%, N=5)	Yes (40%, N=2)	Yes (67%, N=4)
Lightweighting front structures	Yes (100%, N=3)	Yes (100%, N=3)	Yes (33%, N=1)	Yes (100%, N=3)	Yes (50%, N=1)	Yes (67%, N=2)
Magnesium powertrain cast components	Yes (55%, N=16)	Yes (90%, N=26)	Yes (32%, N=9)	Yes (93%, N=26)	Yes (32%, N=8)	Yes (55%, N=16)
Structural cast magnesium development	Yes (90%, N=18)	Yes (100%, N=20)	Yes (19%, N=3)	Yes (100%, N=20)	Yes (60%, N=9)	Yes (58%, N=11)

(1) This question was not posed to the national laboratory researchers participating in this research.
(2) Measured as response to whether participants are willing to collaborate in the future. This is a more precise measurement than in our previous studies where we simply asked the interviewees if collaboration were enhanced.
(3) This question was not applicable to the university and national laboratories participating in this research.
(4) (N) = the number of respondents who answered the question as noted; not the total number of respondents.
(5) This question was not posed during the phase of research that addressed carbon-fiber composite projects.

investigators in the *durability of carbon-fiber composites* felt that the technical objectives were met.

There were mixed replies on whether technical objectives were met in three of the four non-composite projects—*active flexible binder control system for robust stamping*, *magnesium powertrain cast components*, and *structural cast magnesium development*. The majority of investigators in the *active flexible binder control system for robust stamping* and *structural cast magnesium development* project felt the objectives had been met. The response was lower—55 percent—in the *magnesium powertrain cast components* project, which is not expected to be completed until fiscal year 2007. However, many of the investigators who replied "not sure" or "no" qualified their responses. Several commented that the project was still on-going or that they were involved in only one task and could not speak for the entire project. There was unanimous agreement that the technical objectives had been met in the *lightweighting front structures* project.

Almost all respondents, across all projects, believed that that their project had yielded knowledge. Although respondents included representatives from the Big Three firms and material suppliers, only small numbers of respondents—no more than 33% of respondents on any project—believed their company would have participated in the research activity without DOE funding. This question was not posed to the researchers involved in the *modeling of composite materials for energy absorption* project because researchers from two national laboratories conducted this study. Although responses for carbon-fiber composites projects and non-composites projects are similar, it is only the two carbon-fiber projects focused on cost reduction for which all participants agreed that their firm would not have participated absent DOE. Some researchers who believed their firms would have pursued the research without DOE partnerships said that their funding for the activity would be lower. Researchers involved in the carbon-fiber composites projects cited risk, cost, resource or knowledge base required, and uncertainty regarding commercialization as the reasons their firms would not pursue the research without DOE's partnership. Researchers involved in the non-composites noted that DOE's participation is important because it fosters collaboration, attracts major participants, and spreads costs which in reality are too large for any single firm.

All or almost all of the participants in each project believed collaboration was enhanced. (The question specifically asked if participants would be willing to collaborate in the future.) An exception is the *low-cost carbon-fiber development program*, in which half of the participants believed collaboration to have been enhanced. If future collaboration were uncertain, issues related to proprietary concerns and finding the correct mix of technical skills were seen as impediments.

Although the Big Three must cost share in some of the projects, an important assessment is whether the results of these projects—because they dealt with different lightweighting materials—will be incorporated into product design for vehicles. The results are mixed in each case. (The question was posed only to respondents from non-composites projects.) The most positive result, with 62 percent of respondents believing project results would be incorporated into vehicle designs, is from the *structural cast magnesium development* project. Lack of 100% positive response is somewhat surprising for this project because the model year 2006 Corvette

Z'06 has a magnesium engine cradle. The least favorable response (32%) occurred in the *magnesium powertrain cast components* project and could be a reflection of on-going nature of the research.

Finally, there was no consensus among project participants about whether the results of the project were sufficient for carbon fibers and non-composite materials to be a viable option for the automobile sector. Respondents were allowed to respond "yes," "no," or "not sure." Although there was no overwhelming endorsement of a project's contribution to the material's viability in any project, the majority of key managers in two of the five carbon-fiber composites projects and all of the non-composites projects indicated that the results were sufficient for their project's material/technology to be a viable option for the auto industry. The strongest endorsement came in the *low-cost carbon fibers from renewable resources* project, where 83% of respondents believed the results of their project made the material viable to the industry. When asked about barriers to wide-scale introduction of carbon fibers, respondents across the board cited cost and manufacturing/performance issues. The "no" or "not sure" answers could be influenced by the on-going nature of some of the projects or could reflect acknowledgement of remaining barriers.

Where there was not 100 percent agreement on response to a particular metric, there were qualifiers on many of them, e.g., meeting technical objectives, whether the project yielded knowledge, and whether collaboration was enhanced. It may be unrealistic, considering the remaining research to be done on any of the lightweighting materials, to assume that any one of numerous R&D efforts undertaken would be the turning factor for wide-scale adoption by the automobile industry as set in Table 4.17. Here we summarized responses to an open-ended question on barriers to wide-scale introduction of carbon fibers, aluminum, advanced high-strength steel, or magnesium in the manufacture of light-duty vehicles within the U.S. automotive industry.

Costs were identified as a barrier to wide-scale introduction in eight of nine projects. In only one instance, the *lightweighting front structures* project which used advanced high-strength steel, was cost not mentioned. Costs referred generally to the material. Other prominent barriers were manufacturing/performance issues, as well as the corporate culture of the Big Three automakers (e.g., a resistance to change).

Table 4.17: Barriers to Wide-Scale Introduction									
	Research Project								
Barrier Cited	**Composite-intensive body structure development for focal project 3**	**Durability of carbon-fiber composites**	**Low-cost carbon fibers from renewable resources**	**Low-cost carbon-fiber development project**	**Modeling of composite materials for energy absorption**	**Active flexible binder control system for robust stamping**	**Light-weighting front structures**	**Magnesium powertrain cast components**	**Structural cast magnesium development**
Cost	✓	✓	✓	✓	✓	✓		✓	✓
Manufacturing/performance issues	✓	✓		✓	✓	✓	✓	✓	
Corporate culture/resistance to change	✓			✓	✓	✓		✓	
Sufficient availability of lightweighting material		✓	✓						
Adequate material science assessment of low cost carbon fiber			✓						
Market demand for lightweight autos				✓					
Gasoline prices still relatively low				✓		✓			
Downstream conversion processes to deal with low cost carbon forms				✓					
Material uniformity				✓					
Infrastructure demands							✓	✓	✓
Quality, safety standards							✓	✓	
Corrosion								✓	✓
International tariff policies								✓	✓
Competing technologies, materials								✓	✓
Engineering community acceptance									✓
Other									✓

4.2 NATIONAL ACADEMY OF SCIENCES' COMMITTEE ON SCIENCE, ENGINEERING, AND PUBLIC POLICY INDICATORS

The Committee on Science, Engineering, and Public Policy indicators used in our framework are number of publications and presentations, outside review panels, international competitiveness, and recommendations for an appropriate benchmark for gauging international competition.[38]

4.2.1 Publications and presentations

The number of publications ranged over the projects, although each R&D endeavor had publications. Considering the extensive number of presentations and publications, these nine R&D projects have certainly contributed to knowledge benefits. In the *composite-intensive body structure development for focal project 3,* there were 21 journal articles or proceedings. From the *durability of carbon-fiber composites* project, from 1999 forward, there were 19 technical reports; 20 journal articles or proceedings; and 1 dissertation (see Table 4.18).[39] For the *low-cost carbon fiber project*, eight papers were published, one final technical report was submitted to ORNL, and 15 presentations were made at technical conferences that did not produce proceedings. The team on the *low-cost carbon fibers from renewable resources* produced 10 publications and one technical report. There were 8 presentations at technical meetings. In the *modeling of composite materials for energy absorption*, there were 25 publications (from 1999 through 2004) including conference proceedings and technical reports.

There were 7 papers published, 26 technical reports prepared, and 3 presentations from the *active flexible binder control system for robust stamping* project. In the *lightweighting front structures* R&D project, there were 3 papers published, 1 technical report written, and 5 presentations. A total of 23 papers were published, 33 presentations were made, and 3 technical reports were written from the *magnesium powertrain cast components* project. There was extensive publishing in the *structural cast magnesium development* project: a total of 98 journal articles and conference proceedings between 2001 and 2006; 22 presentations were made; and 21 technical reports.[40]

4.2.2 Peer review

None of the projects used an outside peer review team in the format envisioned by National Academy of Sciences. This finding matches our previous evaluations.

However, respondents in the *composite-intensive body structure development for focal project 3* were advised by the Automotive Composites Consortium (ACC) board of directors, the United States Automotive Materials Partnership (USAMP), the FreedomCAR Materials Technical Team (with members from DOE and partners in United States Council for

[38] These are referred to as National Research Council indicators in our previous reports.
[39] A list of publications beginning in 1995 is available.
[40] Several supporting organizations prepared technical reports for their tasks.

Table 4.18: Committee on Science, Engineering, and Public Policy Indicators						
Project	**Number of publications produced including technical reports**	**Number of presentations excluding conference proceedings**	**Did the project use an outside review panel?[1]**	**The United States is leading in research in this field[2]**	**The United States is leading in commercialization in this field[2]**	**The project will improve U.S. international competitiveness[3]**
Composites						
Composite-intensive body structure development for focal project 3	21	--	No	50% (N=3) [4]	0% (N=0)	67%
Durability of carbon-fiber composites	40[5]	--	No	50% (N=3)	17% (N=1)	100%
Low-cost carbon fibers from renewable resources	11	8	No	0% (N=0)	0% (N=0)	100%
Low-cost carbon-fiber development program	9	15	No	50% (N=3)	17% (N=1)	50%
Modeling of composite materials for energy absorption	25	--	No	50% (N=1)	0% (N=0)	100%
Non-Composite Lightweighting Materials Projects						
Active flexible binder control system for robust stamping	33	3	No	33% (N=2)	17% (N=1)	100%
Lightweighting front structures	4	5	No	0% (N=0)	0% (N=0)	67%
Magnesium powertrain cast components	26	33	No	10% (N=3)	11% (N=3)	86%
Structural cast magnesium development	119	22	No	5% (N=1)	10% (N=2)	74%

[1] This question applies to a peer review process as envisioned by the NAS Committee on Science, Engineering, and Public Policy.
[2] Percentage of respondents who selected "leading" in response to the question, "The United States is leading, following, or about even to other countries with respect to …."
[3] Percentage of those responding "strongly agree" or "agree" with statement: "this project will help the U.S. automotive sector to be more competitive in the international market for light-duty vehicles than would have occurred without involvement in the R&D project." Other responses on the five-point Likert-like scale were "no opinion," "disagree," and "strongly disagree." It should be noted that similar results were found to the responses to this statement: "this project will help the U.S. automotive sector to be more competitive in the domestic market for light-duty vehicles than would have occurred without involvement in the R&D project."
[4] N = the number of respondents offering the noted response, not the total number of respondents.
[5] This includes one dissertation.

Automotive Research (USCAR)), and review panels of experts at ORNL. For the *durability of carbon-fiber composites* project, reviews were provided by the Automotive Composites Consortium (ACC) materials team, and at times faculty from the University of Tennessee. The *low-cost carbon fibers from renewable resources* project was also reviewed by ACC working groups and by DOE management.

In the *low-cost carbon fiber* project, review members included the automotive community, DOE and ORNL project staff, and a researcher at Hexcel knowledgeable on the subject matter but not a participating research team member. The *modeling of composite materials for energy absorption* was reviewed by a team that involved DOE laboratories, universities, and the auto industry. This group reviewed progress on a quarterly or semi-annual basis over the course of the research period.

Key managers engaged in *active flexible binder control system for robust stamping* research did not have a peer review. However, they expressed that the team members were provided input from representatives of the auto companies, steel and aluminum companies, and university professors. The *lightweighting front structures* researchers benefited from reviews provided by the Joint Policy Board of the Auto/Steel Partnership, which included product and manufacturing staff from the three automakers, as well as comments provided by Auto/Steel Partnership experts outside the research project.

The *magnesium powertrain cast components* (MPCC) R&D project was organized initially with seven steering committees, staffed with experts from industry, universities, and research laboratories, to provide a review and approve next steps in the research effort. One key manager noted that the testing firms used were accredited and worked independently. Another commented on review by experts affiliated with the Big Three automakers, but not serving on the research effort. In addition, there were annual reviews by USAMP’s Advanced Metals Division (AMD). One investigator noted that conference presentations were reviewed. Several researchers mentioned that their work was reviewed by the MPCC core team or suppliers for the auto industry. Another mentioned DOE review.

The *structural cast magnesium development* team held quarterly and yearly meetings with steering committees and DOE representatives; members of the supply chain provided in-kind review; one respondent had a company representative knowledgeable in the field but not directly involved in the R&D effort provide a review. There was review by the Industry and Government Steering Committee for the Canadian Lightweighting Materials Research Initiative.

4.2.3 International competition and appropriate indicators

We asked several questions with regard to competition. First, we present the interviewees’ perception on the current United States position on research and commercialization. Next we analyze the results to a series of questions on whether the projects will assist the Big Three automakers in the domestic and international markets, as well as whether the private-sector firms involved in the R&D effort might be more competitive in other markets from participation in the project. We conclude with a summary of researchers’ views on appropriate indicators.

It should be pointed out that commercial use of low-cost carbon fiber—with low cost defined by DOE as $3 to $5 per pound—is still in the research phase. There is already commercial use of carbon fibers at a higher cost of $8 per pound.

Composite-intensive body structure development for focal project 3

Fifty percent of the respondents from the *composite-intensive body structure development for focal project 3* endeavor viewed the United States, when compared internationally, as leading in *research* on carbon-fiber composite body structures for use in light-duty vehicles, while the other 50 percent had the impression that the United States was about even with other countries. Of those who felt the United States was about even, they listed European Union (including Germany) as those countries leading. Small cars and sports cars were the responses to our inquiry on what type of light-duty vehicles.

Participants were also asked their assessment of whether the United States was leading, following, or about event with other countries on commercial use of product designs incorporating carbon-fiber composite body structure parts in light-duty vehicles. In contrast to the discussion above, all respondents (N=5) felt that the United States was about even with other countries on *commercial use.* Again, European countries, along with Japan, were listed as leaders in this area. Frames of sports cars, body panels, and other primary and secondary structural components were parts for light-duty vehicles where these countries were leading.

Durability of carbon-fiber composites project

Three respondents (50 percent) felt that the United States was leading in *research* on durability of carbon-fiber composite body structures for light-duty vehicles. One perceived the United States was about even; and two judged that the United States was following. For those who replied that the United States was about even or following, Germany and/or Japan were cited as the leaders in research. Three respondents viewed the research for manufacturing as applicable to sports cars, while one researcher believed that the research was cross-cutting for all automobile types.

We found a different pattern of responses to the question about the Unites States' commercial use of product design using carbon-fiber body structures. Only one researcher thought the United States was leading in commercial use; the remaining respondents (N=5) felt that the United States was following Germany and Japan.

Low-cost carbon fibers from renewable resources

Three of the four persons who responded to the statement describing their impression of *research* on applying low-cost carbon fibers to part designs for light-duty vehicles felt that the United States was about even with other countries; the fourth participant felt that the United States was following other countries. The four felt that Japan was leading in research for mid-sized cars and trucks and hybrid passenger vehicles. All four agreed, however, that the United States was about even with *commercial use* of product designs using low-cost carbon fiber for manufacturing parts for light-duty vehicles. Again, Japan was cited as the country that was leading in commercial use in structural and non-structural components. One respondent noted that, since the goal is reducing weight, items applicable for low-cost carbon fibers are not related to performance or strength.

Low-cost carbon fiber development program
With regard to the low-cost carbon fiber development project, 50 percent of the respondents perceived that the United States was leading in *research* on applying low-cost carbon fibers to part designs for light-duty vehicles, while the remaining 50 percent judged that the United States was about even with other countries. Of those who felt the United States was about even, two referenced Germany as the country leading in research. When asked about research on use for low-cost carbon fibers for manufacturing types of vehicles, one respondent replied that the research could be used for manufacturing all types of vehicles; four respondents felt that the research was for high-end and/or sports cars; the last respondent, trucks, sport utility vehicles, and sports cars.

We found different results from respondents' perceptions of the United States' position internationally on *commercial use* of product designs for light-duty vehicles. Here 50 percent felt that the United States was about even with other countries, 33 percent said the United States is following, and 17 percent viewed the United States as leading. Again, Germany was identified as the country leading in commercial use. When asked about commercial use for manufacturing parts for light-duty vehicles, secondary structural parts was listed most frequently.

Modeling of composite materials for energy absorption
For the *modeling of composite materials for energy absorption*, one respondent felt the United States was leading other countries in *research* on applying low-cost carbon fibers to parts manufacture for light-duty vehicles, while another believed that the United States was about even. Germany and Japan were cited by one respondent indicated as the international leaders in research. With regard to manufacturing of what parts, sports cars were cited, as well as small- and medium-sized cars.

Similarly there was disagreement on how the United States fared internationally with regard to *commercial use*: one indicated about even, the other following. As with research, however, Germany and Japan were cited as leading in commercial use of product design. When asked about commercial use for manufacturing parts for light-duty vehicles, secondary structural parts was once again listed.

Active flexible binder control system for robust stamping
There were divergent responses among those participating in the *active flexible binder control system* on whether the United States was leading in *research* on product design on use of active flexible control system for robust stamping for manufacturing parts for light-duty vehicles. Two respondents felt that the United States was leading, while four felt that the United States was about even with Germany. With regard to manufacturing of what parts, one researcher indicated mid-size cars.

A majority of investigators felt that the United States did not fare well internationally with regard to *commercial use* of product design. Sixty-six percent (N=4) felt that the United States was following other countries, while one indicated that the United States was leading, and another felt that the United States was about even. Germany was again cited as the countries leading on commercial use for automobile body sides.

Lightweight front structures
There were differences among those participating in the *lightweight front structures* project on whether the Untied States was following or about even with other countries in *research* on product design using advanced high-strength steel in manufacturing parts for light-duty vehicles. Two respondents felt that the United States was about even with European Union and Japan. Another researcher felt the United States was following other countries.

Identical views were expressed with regard to *commercial use* of product design using advanced high-strength steel. Sixty-seven percent felt that the United States was about even with European Union (Germany cited specifically) and Japan, while one indicated that the United States was following.

Magnesium powertrain cast components
Fifty-nine percent (N=17) of the researchers in the *magnesium powertrain cast components* viewed that the United States was following in *research* of product design on the use of magnesium for manufacturing parts for light-duty vehicles. Thirty-one percent (N=9) had the opinion that the United States was about even. Only three respondents felt that the United States was leading. Not surprisingly, the countries leading in research are Germany (or the European Union, mentioned in 23 responses). Also listed were China, Japan, Israel, and Australia. In responses to specific components, investigators identified magnesium transmission and door panels. Others answered in more general terms, such as sports cars, trucks, sport utility vehicles, mid-sized cars. One person expressed that magnesium was incorporated in automobiles where performance overrides cost considerations.

Similar views were expressed with regard to *commercial use*. Fifty-seven percent felt that the United States was following, 32 percent said the United States about even with European Union (Germany cited specifically), China, and Japan; and 11 percent replied that the United States was leading. In response to our question on parts, named were[41]

- powertrain
- engine components, e.g., head and valve covers, cylinder blocks, intake manifolds
- oil pans
- structural components
- inner door panels
- crankcases
- brackets
- transfer cases
- cross car beams
- instrument panels
- body panels
- steering column brackets

[41] These responses were provided by those who either felt the United States was “following” and “about even.”

Structural Cast Magnesium Development
Sixty-three percent (N=12) of the investigators in the *structural cast magnesium development* project expressed that the United States was following in *research* for product design. Thirty-two percent (N=6) sensed that the United States was about even with other countries. Only one respondent viewed the United States as leading. The European Union (generally or explicitly Germany), China, Japan, and Israel were mentioned as the countries leading in research. In our follow-up question to what country was in their opinion in research, on manufacturing what type of light-duty vehicle, respondents listed sports and mid-sized cars or sport utility vehicles. On specific components, one respondent offered engines/transmissions and gear boxes, another brought up intake manifolds and control arms.

Comparable results were found on the United States' international role on *commercial use* of product design for light-duty vehicles: 58 percent indicated the United States is following, 32 percent about even, and 10 percent leading. As with research, the European Union and/or Germany specifically and China were cited as leading in commercial use of product designs using structural cast magnesium. Japan was mentioned as closing the gap on commercial use, and Canada was mentioned as leading. When asked about commercial use for manufacturing parts for light-duty vehicles, instrument panels were mentioned by two respondents; others listed intake manifolds, control arms, blocks, cradles, and radiator support.

<u>Incorporation of Results and International Competitiveness</u>
We included a series of statements on whether the R&D project has or will help an individual company and the U.S. automotive sector in general to incorporate the results of the R&D projects into manufacture of light-duty vehicles *more rapidly* than would have occurred without the R&D effort (our research here was gleaned from Link, 1997).[42] We also asked whether the R&D effort would increase the participants' national and international competitiveness. We used a 5-point scale (strongly agree to strongly disagree) for the responses.

The strongly agree or agree responses to the importance of the R&D effort for each project are provided in Table 4.19.[43] The results are generally in agreement among projects that the results *will* help the U.S. automotive industry to incorporate the results into the manufacture of light-duty vehicles and *will* increase the competitiveness of the Big Three in both domestic and international markets. The lower results found in response to the questions on whether the project "has helped" the U.S. automotive sector in general to be more competitive in the domestic and international markets simply recognize that commercialization is far from wide-spread at this point. There is also agreement that the private-sector firms (non-U.S. automakers) involved in the project will be more competitive in other markets besides automobiles.

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[42] The distinction between this measure and the question in the qualitative section on whether the results will be incorporated is a subtle but distinguishable one. In the former we are seeking whether the incorporation will be in general more rapid than would have occurred without the R&D. The latter is whether the results will be incorporated.

[43] Note the wording on each statement as some do not apply to those engaged in the R&D project. For example, there were no private-sector firms involved in the *modeling of composite materials for energy absorption* R&D effort, just as the only private-sector firms participating in the composite-intensive body structure for focal project 3 were the auto sector. Private-sector firms were participants in the *low-cost carbon fibers from renewable resources* and *low-cost carbon-fiber development program*.

Table 4.19: Responses to Importance of R&D Project to Incorporate Results More Quickly and Competitiveness of Firms Involved in R&D Project (Strongly Agree or Agree Responses)					
Responses to Importance of R&D Project to Incorporate Results More Quickly and Increase Competitiveness of Firms Involved in R&D Project (Strongly Agree or Agree Responses)	**Composite-intensive body structure development for focal project 3**	**Durability of carbon-fiber composites(1)**	**Low-cost carbon fibers from renewable resources**	**Low-cost carbon-fiber development project(2)**	**Modeling of composite materials for energy absorption(3)**
This project *will help* the private-sector firm(s) involved in the project to incorporate [project results] into the manufacture of light-duty vehicles more rapidly than would have occurred without involvement in the R&D project.	100%		83%	50%	
This project *has helped* the private-sector firm(s) involved in the project to incorporate [project results] into the manufacture of light-duty vehicles more rapidly than would have occurred without involvement in the R&D project.	50%		0%	17%	
This project *will help* the U.S. automotive sector in general to incorporate [project results] into the manufacture of light-duty vehicles more rapidly than would have occurred without the R&D project.	100%	100%	100%	67%	100%
This project *has helped* the U.S. automotive sector in general incorporate [project results] into manufacture of light-duty vehicles more rapidly than would have occurred without the R&D project.	50%	88%	0%	17%	100%
This project *will help* the private-sector firm(s) involved in the project to be more competitive in the *domestic market* for light-duty vehicles than would have occurred without involvement in the R&D project.	67%		100%	33%	
This project *has helped* the private-sector firm(s) involved in the project to be more competitive in the *domestic market* for light-duty vehicles than would have occurred without involvement in the R&D project.	17%		0%	17%	
This project *will help* the private-sector firm(s) involved in the project to be more competitive in the *international market* for light-duty vehicles than would have occurred without involvement in the R&D project.	67%		100%	33%	
This project *has helped* the private-sector firm(s) involved in the project to be more competitive in the *international market* for light-duty vehicles than would have occurred	17%			17%	

Table 4.19: Responses to Importance of R&D Project to Incorporate Results More Quickly and Competitiveness of Firms Involved in R&D Project (Strongly Agree or Agree Responses)

Responses to Importance of R&D Project to Incorporate Results More Quickly and Increase Competitiveness of Firms Involved in R&D Project (Strongly Agree or Agree Responses)	Composite-intensive body structure development for focal project 3	Durability of carbon-fiber composites(1)	Low-cost carbon fibers from renewable resources	Low-cost carbon-fiber development project(2)	Modeling of composite materials for energy absorption(3)
without involvement in the R&D project.					
This project *will help* the U.S. automotive sector to be more competitive in the *domestic market* for light-duty vehicles than would have occurred without involvement in the R&D project.	83%	100%	100%	33%	100%
This project *has helped* the U.S. automotive sector to be more competitive in the *domestic market* for light-duty vehicles than would have occurred without involvement in the R&D project.	17%	63%		17%	100%
This project *will help* the U.S. automotive sector to be more competitive in the *international market* for light-duty vehicles than would have occurred without involvement in the R&D project.	67%	100%	100%	50%	100%
This project *has helped* the U.S. automotive sector to be more competitive in the *international market* for light-duty vehicles than would have occurred without involvement in the R&D project.	33%	50%	17%	33%	100%
This project *will help* private-sector firm(s) involved in the project be more competitive in other markets for low-cost carbon fiber than would have occurred without involvement in the R&D project.	67%			33%	
This project *has helped* private-sector firm(s) involved in the project be more competitive in other markets for low-cost carbon fiber than would have occurred without involvement in the R&D project.	17%		83%	33%	

(1) There were no private-sector firms, beyond the auto industry, involved in this project.
(2) One key manager qualified his "strongly" agree response with a statement that a significant shift in strategic business objectives, automotive industry acceptance of alternative raw markets, and market conditions and demand would be required.
(3) Recall that only national laboratories were involved in this R&D effort.

Table 4.19: (continued)				
Responses to Importance of R&D Project to Incorporate Results More Quickly and Increase Competitiveness of Firms Involved in R&D Project (Strongly Agree or Agree Responses)	**Active Flexible Binder Control System for Robust Stamping**	**Lightweighting Front Structures**	**Magnesium Powertrain Cast Components**	**Structural Cast Magnesium Development(4)**
This project *will help* the private-sector firm(s) involved in the project to incorporate [project results] into the manufacture of light-duty vehicles more rapidly than would have occurred without involvement in the R&D project.	100%	100%	93%	95%
This project *has helped* the private-sector firm(s) involved in the project to incorporate [project results] into the manufacture of light-duty vehicles more rapidly than would have occurred without involvement in the R&D project.	100%	67%	72%	80%
This project *will help* the U.S. automotive sector in general to incorporate [project results] into the manufacture of light-duty vehicles more rapidly than would have occurred without the R&D project.	100%	100%	97%	95%
This project *has helped* the U.S. automotive sector in general incorporate [project results] into manufacture of light-duty vehicles more rapidly than would have occurred without the R&D project.	100%	100%	59%	80%
This project *will help* the private-sector firm(s) involved in the project to be more competitive in the *domestic market* for light-duty vehicles than would have occurred without involvement in the R&D project.	100%	100%	10%	80%
This project *has helped* the private-sector firm(s) involved in the project to be more competitive in the *domestic market* for light-duty vehicles than would have occurred without involvement in the R&D project.	100%	100%	48%	70%
This project *will help* the private-sector firm(s) involved in the project to be more competitive in the *international market* for light-duty vehicles than would have occurred without involvement in the R&D project.	83%	67%	79%(5)	85%
This project *has helped* the private-sector firm(s) involved in the project to be more competitive in the *international market* for light-duty vehicles than would have occurred without involvement in the R&D project.	83%	67%	45%	70%
This project *will help* the U.S. automotive sector to be more competitive in the *domestic market* for light-duty vehicles than would have occurred without involvement in the R&D project.	100%	100%	83%	85%
This project *has helped* the U.S. automotive sector to be more competitive in the *domestic market* for light-duty vehicles than would have occurred without involvement in the R&D project.	100%	100%	55%	70%

Table 4.19: (continued)				
Responses to Importance of R&D Project to Incorporate Results More Quickly and Increase Competitiveness of Firms Involved in R&D Project (Strongly Agree or Agree Responses)	**Active Flexible Binder Control System for Robust Stamping**	**Lightweighting Front Structures**	**Magnesium Powertrain Cast Components**	**Structural Cast Magnesium Development[(4)]**
This project *will help* the U.S. automotive sector to be more competitive in the *international market* for light-duty vehicles than would have occurred without involvement in the R&D project.	100%	67%	86%[(6)]	74%
This project *has helped* the U.S. automotive sector to be more competitive in the *international market* for light-duty vehicles than would have occurred without involvement in the R&D project.	100%	67%	31%	65%
This project *will help* private-sector firm(s) involved in the project be more competitive in other markets for low-cost carbon fiber than would have occurred without involvement in the R&D project.	100%	33%	82%	80%
This project *has helped* private-sector firm(s) involved in the project be more competitive in other markets for low-cost carbon fiber than would have occurred without involvement in the R&D project.	83%	33%	46%	65%

(4) One participant qualified his agreed response with the comment, "only if they take advantage of the great information developed for them."

(5) One participant noted that his "strongly disagree" response on the international market questions was not due to any shortcoming of the project. Instead, it was based on cost differential and international anti-dumping policy.

(6) One participant qualified his "agree" response with the statement that the international competitiveness would be improved only if the Big Three make a commitment to use magnesium in their powertrains.

Benchmark Indicators

We included an open-ended question on what measure is appropriate for gauging U.S. competitiveness in this area. The overwhelming majority of the answers from the *carbon-fiber composites* evaluation, combining response from all five R&D projects, were: (1) the number or market share of vehicles that have incorporated carbon fibers or (2) the amount, e.g. weight of carbon fibers, in a vehicle[44] as measures. These were the majority of indicators in the *durability of carbon-fiber composites*, *low-cost carbon fibers*, *low-cost carbon fibers from renewable resources*, and the *modeling of composite materials for energy absorption* project. Other indicators offered were research and development spending on incorporation of carbon fibers; fuel savings from using carbon fibers; predictive modeling efforts on R&D; and government incentives for the automotive manufacturers to incorporate non-traditional materials into component parts.

The majority of investigators in the *active flexible binder control system for robust stamping* listed number of systems used in production. One respondent felt that corporate understanding, support, and determination to use research results could serve as an indicator for gauging U.S. competitiveness. The researchers engaged in the *lightweighting front structures* project named (1) percentage advanced high-strength steel content of vehicles and (2) number of parts using AHSS.

Several responses were offered from the *magnesium powertrain cast components* project. Four broad groupings were

- pounds of magnesium per vehicle
- number of magnesium applications (components) per vehicle
- funds spent on research or support to magnesium casting/forming sector
- cost (effectiveness of magnesium use, vehicle, magnesium)

Other indicators include increase in magnesium applications per vehicle; number of magnesium suppliers; aggregate weight reduction at lower cost per pound of magnesium; sales of vehicles with magnesium components; types of new applications of magnesium per vehicle; reputation of magnesium end users; weight reduction in pounds per vehicle with magnesium components; fuel economy; and continued use of magnesium after market introduction.

From the *structural cast magnesium development* effort, indicators fell into three themes: amount of magnesium per vehicle, amount or number of R&D programs on magnesium, or type of auto parts using magnesium.

4.3 QUANTIFIABLE BENEFITS

There are several commonly accepted metrics of knowledge derived from an R&D effort in addition to publications and presentations. These metrics are presented here and summarized in Table 4.20. The major difference between the two quantifiable benefits for the composites

[44] One researcher worded the response slightly different: this person considered the weight reduction of the vehicle due to use of carbon fibers.

Table 4.20: Quantifiable Benefits					
Project	Student involvement (year of project/# of students)	Degrees sought by students	Patents Applied for/ Received	Copyrights Applied for/ Received	Software Developed and Commercialized
Composites					
Composite-intensive body structure development for focal project 3	1/3 2/1 3/2 4/2 5/1	Master's, Ph.D, or Post-doctoral	No	No	No
Durability of carbon-fiber composites	1/1 2/2 3/2 4/2 5/2	Master's and Ph.D.	No	No	No
Low-cost carbon fiber from renewable resources	3/1 4/1 5/1	Ph.D.	Yes[(2)]	No	No
Low-cost carbon fiber development program	1/3 2/4 3/5 4/3 5/2	Master's and Ph.D.	No	Internal to firm	No
Modeling of composite materials for energy absorption	1/4 2/4 3/4 4/4 5/3	Master's and Ph.D.	No	No	Yes
Non-Composite Lightweighting Materials Projects					
Active flexible binder control system for robust stamping	1/4 2/4 3/6	Master's and Ph.D.	No[(3)]	No	See text summary
Lightweighting front structures	1/3	Master's	No	No	Yes[(4)]
Magnesium powertrain cast components	1/0 2/0 3/1 4/6 5/15 6/11	Bachelor's, Master's, and Ph.D.	Yes[(5)]	No[(6)]	See text summary
Structural cast magnesium development	1/7 2/11 3/18 4/21 5/30	Bachelor's, Master's, and Ph.D.	No[(7)]	No	See text summary

[(1)] One researcher is anticipating developing and commercializing software in the future.
[(2)] Another application for a patent has been filed.
[(3)] One respondent anticipates his firm applying for two patents sometime in 2006.
[(4)] Developed, but not commercialized.
[(5)] One respondent anticipates his firm applying for a patent in 2007; another anticipates applying for two patents in 2006; and a third anticipates applying for a patent although the year is not certain.
[(6)] One respondent anticipates his firm applying for two copyrights sometime in 2006.
[(7)] One respondent anticipates his firm applying for a patent sometime in 2006.

projects versus the non-composites projects is that we include undergraduate students in the second set of evaluations.

The number of graduate students engaged in any of the carbon-fiber composites projects ranged from 1 to 5. These projects engaged Master's, Ph.D., and post-doctoral students. For the non-composites projects, data include bachelor's as well as Master's and Ph.D. students. Each non-composites project engaged students, with the numbers ranging from zero (in early stages of the *magnesium powertrain cast components* project) to 21. In some cases—especially the two magnesium projects—the number of graduate students rose significantly in the latter years of the R&D effort. This reflects the university's participation in the activity, as well as the expanded R&D tasks.

Other metrics concern patents, copyrights, and commercialization of software packages. There were no patents, copyrights, and software packages developed and commercialized in the *composite-intensive body structure development for focal project 3* R&D effort. One respondent did anticipate developing software in the future. In the *low-cost carbon fiber development program*, the private-sector firm received an internal copyright in 2001. This project did not involve software development or modification.

There was one patent applied for and approved in the *low-cost carbon fiber from renewable resources* project and one outstanding patent application at the time of this evaluation. It is anticipated that another patent application will be submitted in 2006 or 2007. No software was used in this R&D project. There were no patents or copyrights applied for or received in the *durability of carbon-fiber composites project* or in the *modeling of composite materials for energy absorption project*.

The objective of the *modeling of composite materials for energy absorption* was to develop analytical and numerical tools, including software. The researchers modified existing tools for this effort. When asked what percentage of modification was needed to make the tools applicable to this R&D effort, responses ranged from 21-30 percent modification to greater than 50 percent modification. The greatest challenges faced in the modification process were (1) material model implementation and material failure and (2) determining the physics necessary to be put into computer code. Part of the software packages developed as a result of the R&D project were commercialized and introduced into the marketplace between 2001 and 2004.

As evidenced here, not every research project will result in deliverables or products that will be commercialized. Regardless, it is important to ascertain the reception of these items by the auto industry and equally important to determine whether the automakers and/or their suppliers make use in their decision-making processes for lightweighting vehicles. Therefore, of interest in the overall evaluation effort is the reaction of the Big Three automakers to the software package or other deliverables finalized from the project.

The participants in the *modeling of composite materials for energy absorption* reported that the (1) reception from the automobile industry was positive and (2) results are being used in composite crash analysis and design.

The output of the *durability of carbon fibers composites* was durability-based guidelines. The results were presented to the Big Three automakers at various times throughout the project period.[45] Eighty-eight percent (N=7) of the researchers responded to the question on their perception of how the guidelines had been received by the Big Three; all felt that the guidelines had been well-received by the Big Three, providing the automakers with valuable information. In addition, 88 percent of the respondents (N=7) felt that the information will be used by the Big Three.

The participants in the *active flexible binder control system for robust stamping* have not applied for any patents or copyrights; however, one researcher anticipates applying for two patents sometime during 2006. There were four deliverables from this research activity: computer simulation/optimization codes, design guidelines for flexible binders, 26-cylinder binder load control unit, and control algorithm for non-linear systems. All have been delivered in draft to the Big Three automakers. Commercialization of some of these deliverables would not be expected. However, one interest is to determine the reception of these items by the auto industry and to find out whether the automakers and/or their suppliers will make use in their decision-making processes for incorporating aluminum in production (see Table 4.21).

A third of the investigators thought the computer simulation/optimization codes would *not* be commercialized. The two researchers who felt there would be commercialization predicted that to occur sometime in 2006. All expressed a favorable reaction by the Big Three automakers to the codes, but only 50 percent of the respondents felt the product would be used by the Big Three in their decision-making process on incorporating aluminum.

Only *one* respondent viewed that the design guidelines for flexible binders would be commercialized, that the product was favorably received by the Big Three, or that it would be employed by the Big Three in decision-making process. Anticipated commercialization was 2008.

Similar results were found for the 26-cylinder binder load control unit: only one researcher sensed the product would be commercialized (sometime in 2006) and that the reaction was favorable (one investigator felt the reaction was indifferent). There was slightly more positive belief that the unit would be used by the Big Three: one respondent said yes, and one said that there was a 50/50 chance it would be used by the Big Three. The remainder (N=2) said it would be not.

The final deliverable was control algorithm for non-linear systems. This product fared reasonably well in all categories: 60 percent (N=3) indicated the product would be commercialized, all thought the product was favorably received by the Big Three (N=5); two felt certain it would be used by the Big Three with another considering it “likely” that it would be used. One participant was negative on the use, while the last participant indicated “not sure.”

[45] The final report was completed during this evaluation.

Table 4.21: Products of Active Flexible Binder Control System for Robust Stamping				
Products of R&D effort	**Will this product be commercialized?**	**If commercialized, anticipated date of commercialization**	**What was the reaction of the Big Three to the draft product?**	**In your opinion, will product be used by Big Three in decision-making process on incorporating aluminum in production line?**
Computer simulation/optimization codes	No (50%, N=3)	2006	Favorable (100%, N=6)	Yes (50%, N=3)
Design guidelines for flexible binders	No (80%, N=4)	2008	Unfavorable or indifferent (75%, N=3)	No or less likely (75%, N=3)
26-cylinder binder load control unit	No (80%, N=4)	2006	Unfavorable or indifferent (75%, N=3)	No (50%, N=2)
Control algorithm for non-linear systems	Yes (60%, N=3)	2008	Favorable (100%, N=5)	Yes or likely (60%, N=3)

There were several comments to the question on what automobile component they anticipate the Big Three automakers would manufacture as a result of this R&D effort. Those offered are

- sheet-metal panels
- autobody stamping (cited by two participants)
- the more difficult prototype parts, such as fenders, liftgates, closure panels, and structure parts currently made of steel

One objective of the *lightweighting front structures* project was to develop a knowledge-based design tool that has since been distributed to the Big Three automakers. Their reaction was generally favorable. Specifically, one respondent noted that it was a useful tool that will aid in design-of-experiment exercises; another participant felt that the Big Three were interested in the methodology of the tool. Two of the investigators indicated that the Big Three would use the tool; one pointed to manufacturing body structures, in model year 2006 and beyond.

There was one patent applied for in 2005 in the *magnesium powertrain cast components,* although other researchers anticipate applying sometime in 2006, 2007, or later. In addition, it is anticipated that two copyrights will be applied for sometime in 2006.

As expected with a large research project as this, there were multiple deliverables: some with the potential for commercialization, others not.[46] The responses to the questions on likelihood of commercialization, whether drafts have been presented to the Big Three, and whether the deliverables will be used by the Big Three in their decision-making process on incorporating magnesium into automotive production are presented in Table 4.22. Although some products are in process—the project had not been completed at the time of data collection—the automakers have seen drafts, if not the final product. It should be noted that there will not 29 responses for any given deliverable, although there are a total of 29 respondents, because team member were not all involved with each of the deliverables.

In response to our question on what automobile component the investigators anticipate the Big Three automakers would manufacture as a result of the R&D effort, several components were offered, indicating general agreement among all researchers regardless of their firm/industrial sector (in parenthesis is the number of times a component was mentioned):

- oil pans (17)
- front engine cover (16)
- engine blocks (12)
- rear seal retainer (8)
- powertrain (4)
- bed plates (3)
- transmission case (3)
- valve covers (2)
- other (small non-structural components, cylinder block, intake manifold, deck plates, rocker arms, drain train, suspension components, creep resistant, chassis components, cradle).

[46] We should note that one researcher commented that the intent of the magnesium powertrain cast component research effort was *not* to commercialize components but to determine feasibility of incorporating magnesium into powertrains.

Table 4.22: Products of Magnesium Powertrain Cast Components R&D Effort[1]				
Products of R&D effort	**Will this product be commercialized?**	**If commercialized, anticipated date of commercialization.**	**What was the reaction of the Big Three to the draft product?**	**In your opinion, will product be used by the Big Three in their decision-making process on incorporating magnesium into automotive production?**
1. alloy testing, selection and database	Yes (64%, N=9) No (36%, N=5)	2006 (N=2) 2007 (N=3) 2008 (N=1)	Favorable (55%, N=6) Very favorable (45%, N=5)	Yes (100%, N=13)
a. data	Yes (50%, N=1) No (50%, N=1)	2006 (N=2)	Very favorable (100%, N=1)	Yes (50%, N=1) No (50%, N=1)
b. database architecture	Yes (100%, N=2)	Yes (100%, N=2)	No response	Yes (100%, N=1)
2. magnesium-intensive engine (MIE) design	Yes (33%, N=4) No (67%, N=8);	2007 (N=1) 2008 (N=1) 2020 (N=1)[3]	Favorable (43%, N=3) Very favorable (29%, N=2); Indifferent (28%, N=2)	Yes (90%, N=9) No (10%, N=1)
3. coolant-corrosion investigation/evaluation	Yes (58%, N=7) No (42%, N=5)	2006 (N=3) 2008 (N=2)[3]	Favorable (86%, N=6) Very favorable (14%, N=1)	Yes (100%, N=12)
4. cost model	Yes (23%, N=3) No (77%, N=10);	2006 (N=1)[3]	Favorable (83%, N=5); Indifferent (17%, N=1)	Yes (100%, N=7)
5. current and future research for North America	Yes (50%, N=4) No (50%, N=4)	2007 (N=1) 2008 (N=3)	Favorable (60%, N=3) Very favorable (20%, N=1); Indifferent (20%, N=1)	Yes (100%, N=11)
a. phase equilibrium and computational thermodynamics	Yes (67%, N=3) No (33%, N=1)	No dates offered	Favorable (50%, N=1) Very favorable (50%, N=1)	Yes (100%, N=2)
b. casting, solidification behavior (hot tearing) and microstructure	No (100%, N=3)	No response	No response	No response
c. alloy development and structure-property relationships	Yes (100%,N=3)	2008 (N=1)	Favorable (100%, N=1)	Yes (100%, N=1)
d. creep and bolt-load retention	Yes (100%, N=3)	2007 (N=1)	Favorable (50%, N=1) Very favorable (50%, N=1)	Yes (100%, N=2)
e. corrosion behavior and protection	Yes (80%, N=4) No (20%, N=1)	2006 (N=1) 2008 (N=1)	Very favorable (75%, N=3); Indifferent (25%, N=1)	Yes (80%, N=4) No (20%, N=1)

Table 4.22: Products of Magnesium Powertrain Cast Components R&D Effort[1]				
Products of R&D effort	**Will this product be commercialized?**	**If commercialized, anticipated date of commercialization.**	**What was the reaction of the Big Three to the draft product?**	**In your opinion, will product be used by the Big Three in their decision-making process on incorporating magnesium into automotive production?**
f. alloy recycling	Yes (100%, N=2)	2007 (N=1)	Favorable (50%, N=1); Indifferent (50%, N=1)	Yes (50%, N=1) No (50%, N=1)
6. component filling and solidification models[2]	Yes (58%, N=7) No (42%, N=5)	2006 (N=2) 2007 (N=1)	Favorable (57%, N=4) Very favorable (29%, N=2); Indifferent (14%, N=1)	Yes (69%, N=9) No (31%, N=4)
7. component tooling	Yes (75%, N=6) No (25%, N=2)	2008 (N=5)[3]	Favorable (83%, N=5); Indifferent (17%, N=1)	Yes (91%, N=10) No (9%, N=1)
a. cylinder block	Yes (50%, N=1) No (50%, N=1)	No date offered	Favorable (50%, N=1); Indifferent (50%, N=1)	Yes (50%, N=1) No (50%, N=1)
b. structural oil pan	Yes (100%, N=2)	No date offered	Favorable (100%, N=2)	Yes (100%, N=2)
c. front engine cover	Yes (100%, N=2)	No date offered	Favorable (50%, N=1); Indifferent (50%, N=1)	Yes (50%, N=1) No (50%, N=1)
d. rear seal carrier	Yes (100%, N=2)	2006 (N=1)	Favorable (100%, N=2)	Yes (100%, N=2)
8. FEA and optimization of MIE design	Yes (27%, N=3) No (83%, N=8);	2008 (N=1)[3]	Favorable (100%, N=5)	Yes (100%, N=7)
9. MPCC website	Yes (27%, N=3) No (73%, N=8);	2006 (N=2) 2008 (N=1)	Favorable (60%, N=3) Very favorable (20%, N=1); Indifferent (20%, N=1)	Yes (57%, N=4) No (43%, N=3)
10. excised specimen testing	Yes (78%, N=7) No (22%, N=2)	2006 (N=2) 2007 (N=3) 2008 (N=2)	Favorable (33%, N=1) Very favorable (67%, N=2)	Yes (100%, N=11)
11. engine durability testing	Yes (60%, N=6) No (40%, N=4)	2006 (N=2) 2007 (N=1) 2008 (N=1)[3]	Favorable (50%, N=2) Very favorable (50%, N=2)	Yes (100%, N=12)

[1] Some investigators answered for the overall product deliverable, rather than the individual parts. Both responses are reported here. The research team, principal investigator, and project manager consulted to compile the list of product deliverables presented in this table. One respondent, separately, listed resonant testing. The respondent mentioned that various forms of the testing are commercially available now, the reaction of the Big Three has gone from indifferent to favorable, and that the testing would be used by the Big Three in their decision-making process for lightweighting vehicles.
[2] One researcher responded yes to the question on whether the following items under the component filling and solidification models would be commercialized: cylinder block, structural oil pan, front engine cover, and rear seal carrier.
[3] Anticipated commercialization date as "unknown" was offered by researchers.

There were no copyrights applied for or received from research products from the *structural cast magnesium development* effort. One firm anticipates applying for a patent sometime in 2006. However, that research venture had several deliverables: magnesium alloy database, radioscopic standard for magnesium castings, cost model, failure model, and assessment of magnesium (report titled, “Magnesium 2020”) (see DOE, 2002; DOE, 2003; U.S. DOE, 2004c; U.S. DOE, 2005a). Drafts of the five outputs have been presented to the Big Three automakers. It should also be recalled that General Motors has already incorporated results of the overall R&D effort in the model year 2006 Corvette Z’06 engine cradle. Broader usage of the deliverables is the question addressed here.

The responses to this line of questioning are presented in Table 4.23. It should be noted that there will not be 20 responses to inquiry on deliverables as some team members were focused on development of one product, but not all of them. In addition, some respondents were not familiar with whether a product would be commercialized, but were sufficiently knowledgeable on the reaction of the Big Three to product delivery and future use. Based on the responses, it appears the commercialization of the (1) cost model and (2) Magnesium 2020 report are unlikely. There is greater potential for commercializing the magnesium alloy database and radioscopic standard. There was less certainty on the failure model. Overall the products were favorably received by the auto sector, and have potential to be used in decision-making beyond the Corvette Z’06 either by the Big Three automakers or suppliers.

When followed up with a question on what automobile component the investigators anticipate the Big Three automakers would manufacture as a result of the R&D effort, several components were offered (in parenthesis is the number of times a component was mentioned):

- cradles (11)
- wheels (4)
- suspension, knuckles (4)
- control arms (3)
- front end, including bumper beans, underhood applications (3)
- interior, including steering wheel, instrument panels (3)
- cross members (2)
- structural components (2)
- other (powertrain, doors, subframes, castings) (4)

Table 4.23: Products of Structural Cast Magnesium Development R&D Effort[1]				
Products of R&D effort	**Will this product be commercialized?**	**If commercialized, anticipated date of commercialization.**	**What was the reaction of the Big Three to the draft product?**	**In your opinion, will product be used by the Big Three beyond the Corvette Z'06?**
1. Magnesium alloy database	Yes (100%, N=4)	2006 or 2007	Favorable or very favorable (100%, N=13)	Yes (100%, N=13)[2]
2. Radioscopic standard for magnesium castings	Yes (64%, 7 of 11 responses)[3]	Immediately to 2010	Favorable or very favorable (92%, 11 of 12; 1 indifferent)	Yes (93%, 13 of 14 responses)[4]
3. Cost model	No (90%, 9 of 10 responses; 1 yes)	2007	Favorable or very favorable (75%, 6 of 8; 2 indifferent)	Yes (86%, 6 of 7; 1 no)
4. Failure model	Yes (50%, 5 of 10; 30% no; 20%, don't know or possibly)	2006-2010	Favorable or very favorable (100%, N=4)	Yes (100%, N=12)
5. Magnesium 2020 assessment	No (58%, 7 of 12; 42% yes, 5 of 12)	2005 to 2008	Favorable or very favorable (90%, 9 of 10; unfavorable 10%, 1)	Yes (92%, 12 of 13; no 8%, 1)

(1) Two respondents commented that molds developed under the R&D effort could be commercialized.
(2) One noted that suppliers would use the database as well as the Big Three.
(3) Three respondents expressed the possibility that the product could be commercialized. One investigator responded no.
(4) One respondent felt there was a greater chance of application if ASTM adopted the standard.

4.3.1 Summary of Committee on Science, Engineering, and Public Policy indicators and quantitative benefits

Publications, including technical reports, and number of presentations without conference proceedings varied considerably, but the numbers appear dependent primarily on the number of participants per research project. It is noteworthy that projects with a heavy involvement from the private sector can publish extensively. This is somewhat different from our previous evaluations and once again confirms that the corporate culture defines the importance of publications. In at least one situation—*low-cost carbon-fiber development* program—publishing the results was a corporate expectation.

Number of publications is often used as an employee evaluation metric at national laboratories so large number of publications would be expected from projects involving the laboratories, such as the *durability of carbon-fiber composites* and *modeling of composite materials for energy absorption*, despite the smaller number of researchers on the R&D effort.

Finally, the numbers for the *magnesium powertrain cast components* appear reflective of the number of participants, although we would expect these numbers to increase as the project reaches its conclusion. The *structural cast magnesium development* project echoes our comment on corporate structure and number of participants. Note that the national laboratories are not involved as key managers or researchers in these two projects.

Like our previous analyses, none of the projects had outside review panels as envisioned by the National Academy of Sciences. For several years, an independent outside panel convened by the National Academy of Sciences' National Research Council reviewed FreedomCAR's predecessor, Partnership for a New Generation of Vehicles (PNGV) (NRC, 2001b).[47] In the fall of 2004, the Board on Energy and Environmental Systems assembled a team to review FreedomCAR and issued its first report in 2005 (NRC, 2005). Regardless, each project had the benefits of outside review albeit by members of the ACC, DOE, USAMP, Auto/Steel Partnership, or experts within a firm but not an active participant in the R&D effort.

There were mixed results on four of the five projects on whether the United States is leading in research on low-cost carbon fibers: 50 percent of the respondents indicated yes in (1) *composite-intensive body structure development for focal project 3*; (2) *durability of carbon-fiber composites*; (3) *low-cost carbon-fiber development*, and (4) *modeling of composite materials for energy absorption*. In the *low-cost carbon fibers from renewable resources* project, the researchers felt the United States was about even or following other countries.

Not any of the researchers thought the United States was leading in research on any of the non-composite research projects. With regard to commercialization, researchers in only one project—*modeling of composite materials for energy absorption*—felt that the United States was leading in commercialization.

There was agreement among all nine projects that the results will improve the United States' international competitiveness. In general, respondents felt the project will help the private-sector

[47] Seven reviews were conducted on PNGV by NRC's Board on Energy and Environmental Systems.

firms (as opposed to the U.S. automotive sector) to incorporate project results into the manufacturing of light-duty vehicles more rapidly than would have occurred without involvement in the R&D project. In only one project was the percentage response at 50 percent—*low-cost carbon-fiber development* project. The remaining projects were 83 percent or higher.

General accord was observed on whether the project will help the United States automotive sector in general to incorporate results into the manufacture of light-duty vehicles *more rapidly* than would have occurred without the R&D project. There were disparate views on whether the research project will help the private-sector firms involved in the project to incorporate the results into the manufacturing of light-duty vehicles more rapidly than would have occurred without involvement in the project.

There was agreement generally among the participants in the composites projects that a benchmark indicator should be number of vehicles in the marketplace incorporating carbon fibers as a component or the quantity of carbon fibers in vehicles. Other projects suggested a quantity indicator as well, albeit pounds of magnesium per vehicle, percentage of advanced high-strength steel, number of applications per vehicle, aggregate weight reduction due to incorporating a lighter weight material.

It should *not* be an expectation that patents, copyrights, or software evolve from every R&D project funded by ALM and to an extent the same can be said of graduate student involvement. That patents and copyrights were applied for and received, and software tools were commercialized in three of the five composite projects is a significant intellectual contribution. That commercialization will not occur for many products of the *active flexible binder control system* or only a portion of the products from the structural cast magnesium product should not be perceived as a reflection of the inadequacy of the project's efforts to incorporate aluminum or magnesium into automobiles. That there is disagreement about commercialization in the *magnesium powertrain cast components* may reflect that there are numerous products from this research effort, the effort is still ongoing, and commercialization should in fact not be an expectation for everything resulting from the project.

Even in projects that did not include a university as a partner, graduate students were supported (low-cost carbon fiber development program and *modeling of composite materials for energy absorption*, *active flexible binder control system for robust stamping*, *lightweighting front structures*). These knowledge benefits are noteworthy, particularly when added to the knowledge gains identified in the qualitative assessment.

4.4 ECONOMIC ANALYSES

As outlined in Section 2.3, the economic analyses have two monetary components. The first component, addressed in Sections 4.4.1 through 4.4.5, pertains to the benefits derived from the commercialization of the technologies; we calculated a social benefit-cost ratio. The higher the market penetration of new vehicles that have benefited from the R&D projects, the greater the benefits to be attributed to the projects.[48] The second monetary calculation relates to the person-year and cost savings analysis. These components are covered in Section 4.4.6.

4.4.1 Social benefit-cost analysis

The benefit estimation in the social benefit-cost approach has three components. The first component, discussed in Section 4.4.2, addresses the potential market penetration of new vehicles that contain materials and/or parts that can be directly attributed to the projects. The project benefits are estimated based on the specific contribution obtained using a Delphi survey that the project made to the commercialization of a technology application. For this project, market penetration rates are forecast out to the year 2030, with the consideration of starting year of benefits two years into the future, i.e., 2007, to include implementation costs due to adoption of the technology. The second component addresses benefits gained as the new vehicles are adopted in the marketplace. As laid out in Section 4.4.3, three categories of benefits are assessed: energy, environmental, and security for mainly four life-cycle stages (i.e., extraction, processing, manufacturing, and use) under three different benefit scenarios. The third component, described in Section 4.4.4, combines the results of the market penetration forecast and the benefits list into three benefit scenarios, where benefits are projected annually out to the year 2030 and discounted to net present value terms (i.e., in 2005 dollars). Using the estimated net present value of the project benefits and costs, benefit-cost ratios for the projects under three different scenarios are finally estimated in Section 4.4.5.

It should be pointed out that the benefits and costs assessed here are social benefits and costs, not the benefits and costs that would be considered by a private-sector firm in determining potential returns-on-investment associated with these projects. Included in the social benefits category are benefits that are rarely if ever included in private sector financial calculations, such as social environmental benefits derived from the reduction of the emission of greenhouse gases and criteria air pollutants. In addition, in this evaluation we have included national security benefits associated with reducing the nation's need for oil. Because the category of social benefits, by definition, encompasses a broader range of benefits than does the category of private sector benefits, the magnitude of the social benefits gained from these types of government activities are typically much larger than benefits potentially accruable to firms.

By calculating a social benefit-cost ratio, we are not calculating a return-on-investment that participating private sector companies might receive from commercialization of project products. We do not know how much it will cost companies to commercialize and market new products, or to what extent the use of products in new vehicles will increase market share of these vehicles for those companies. We also do not know if use of the products in new vehicles will allow companies to increase prices of their vehicles, thereby possibly increasing profits gained from selling each new vehicle. Without such knowledge, we have no basis upon which to calculate private sector return-on-investment rates associated with these projects.

[48] We are referring particularly to vehicles that have higher amounts of a specific lightweighting material due to successful project completion.

To estimate oil security benefits, we looked to work by Greene and Leiby (2006), who estimate benefits associated with reducing oil imports into the United States. These authors applied different methods to estimate a range of oil security benefits, but recommended most highly their Method 1 which measures security benefits as the reductions in the following three types of economic costs caused by oil supply disruptions: (i) transfer of wealth from the US economy to oil exporting countries, (ii) producers' and consumers' surplus losses as a result of the higher oil prices, and (iii) macroeconomic disruption losses resulting from oil price shocks. In addition, this study uses the latest EIA 2006 Annual Energy Outlook projections of different oil price scenarios (where world oil prices varied from a low of $29/barrel in 2015 to $90/barrel in 2030). Following this advice, we translated their low and high oil security benefit estimates into low and high oil security benefits per barrel of oil (based upon present value estimates for dollars saved—$35 to $58B and barrels of oil saved, 4 billion, see Table E.S.6). Thus, our low and high estimates of the benefits to oil security of reducing consumption of a barrel of oil are $9 per barrel and $15 per barrel, with an average benefit of $12 per barrel.

4.4.2 Market penetration

Four Delphi exercises were designed and implemented to collect information for the benefit-cost analysis. Delphi exercises involve panels of experts who collectively offer a great deal of expertise to help assess very difficult issues. In this case, the experts were contacted to judge the amount of lightweighting materials—carbon fiber, aluminum, magnesium, and lightweighting steel—that will be in new light-duty vehicles sold in the United States between the year 2005 and the year 2030, in five year increments. The experts were also asked to judge the influences of the DOE ALM effort on the market penetration of these materials and to judge thresholds of gasoline prices where market penetration of these materials could be expected to increase substantially.

Names of between ten and twenty-eight experts in each of the four material areas were obtained from various sources (e.g., personal contacts, contacts of other experts in the field). Initially, each person was contacted by email. Second contacts were also conducted using email. Subsequent contacts were made by phone.

Overall, the numbers of experts who participated in each Delphi were as follows: CFRP – six; aluminum – three; magnesium – four; and lightweighting steel – three. Most experts contacted did not respond to emails or phone calls. Several who did respond declined to participate for a variety of reasons, including concerns about company proprietary information, lack of time, and perceived lack of expertise to satisfactorily answer the Delphi questions.

The Delphi instruments, which were emailed to the respondents, consisted of two general sections and three specific sections. The first section served to create a context for this exercise by providing short descriptions of all DOE projects in a specific materials area that were funded during the past five years. Those projects for which the respondents would be asked to provide judgments about were highlighted—five in the CFRP area, one in the aluminum area, two in the magnesium area, and one in the lightweighting steel area (Table E.S.1 contains the names and descriptions of the highlighted projects). The second section asked the respondents to provide remarks about other non-DOE funded lightweighting materials research in the United States and the rest of the world that could be influencing the market penetration of lightweighting materials in light-duty vehicles in the United States.

The third section asked respondents to estimate by weight the amount of lightweighting materials in new light-duty vehicles sold from 2005 to 2030. In the CFRP Delphi, experts estimated weight separately for 1) body components, 2) chassis components, and 3) powertrain components. In the other three areas, experts estimated the total weight of materials regardless of type of component.

A second set of questions in the third section addressed the influences upon these market penetration rates of all lightweighting materials research around the world in the area being addressed (e.g., all CFRP research, all magnesium research), all of DOE's lightweighting materials research in the area, and finally for each of the highlighted projects (e.g., five in the CFRP area, one in the aluminum area). The third and last set of questions inquired about how high gasoline prices would have to be over the 2005 to 2030 time period to ensure that components made from the lightweighting materials could be cost-competitive with traditional steel-based components.

Tables 4.24, 4.25, 4.26, and 4.27 present comments provided by the respondents about non-DOE research in the United States and the rest of the world in the CFRP, aluminum, magnesium and lightweighting steel areas, respectively.

Overall, there does not seem to be a great deal of non-DOE funded CFRP research in the United States. The same appears to be true in the aluminum and magnesium areas. However, much research CFRP appears to be going on in Europe and Japan, with Europe also leading in research in the aluminum and magnesium areas. The United States does have very active non-DOE sponsored research in lightweighting steel that involves automobile manufacturers and aluminum suppliers. Europe and Japan are strong competitors in this area as well.

Tables 4.28, 4.29, and 4.30 present averages of the estimates provided by the respondents related to CFRP body components, chassis components, and powertrain components, respectively.[49] The estimated market penetration rates are low for all three types of components in the near-term. These rates approach double digits in the longer-term. The respondents expect CFRP materials to make the most impact in body panels, least in the powertrain components.

Worldwide, CFRP research is expected to heavily influence the market penetration of CFRP components in light-duty vehicles into the future. DOE's influence is estimated to be substantial, highest with respect to body panels and lowest with respect to powertrain components. Each of the five projects is judged to be influential. The *Focal project 3* is most influential in the body component area. The *low-cost carbon-fiber development* project is most influential in the chassis

[49] In two cases, one related to market penetration and one related to gasoline threshold prices, outlying estimates were dropped.

Table 4.24: Summary of Comments about non-DOE CFRP Research	
Non-DOE CFRP Research in the U.S.	**Non-DOE CFRP Research Outside U.S.**
General Assessment: There is only limited non-DOE CFRP R&D taking place in the U.S., mostly in defense, aerospace, specialty vehicles (e.g., race cars, experimental vehicles), and nanocomposites applications. Specific Activities: • Ford US - development of carbon fiber (CF)/polyamides(PA) sheet stamping and over-injection, research stage, high volume technology • Ford GT CF composite rear deck lid and bucket seats feature carbon-fiber shells, in production, low volume technology • Dodge viper CFRP work, low volume technology • HyperCar concept studies for CFRP usage with fuel cell drive trains (revolution SUV study), concept stage (no working prototype) • Visteon produced a CFRP-intensive pickup. • Delphi was involved in CFRP composite part development. • Fiberforge process development (netshape tailored thermoplastic (PA) and CF blanks for stamp-forming, in development, high volume focused, first non-automotive application imminent	General Assessment: European and Japanese OEMs, fiber manufacturers, and contract research laboratories are quite proactive in the lightweighting materials research, due to more pressure on improved fuel economy and reduced emissions. Specific Activities: • AstonMartin Vanquish braided A-pillars, central tunnel section, front crash section, suspension post strut brace etc, in production at low volumes • Porsche GT autoclave processed CFRP body structure (core cell of car), stamped CF/PA arm rest structures, working with ATR Italy, in production, low volume focused • Development of a CF-P4 cell at the University of Nottingham, UK, research stage • Development of a netshape preforming computerized numerical controls cell at the University of Cranfield, UK, originally for aerospace with automotive potential • FastFrames project at the University of Cranfield, UK, research project • Coriolis composites (France) 7-axis unidirectional tow placement cell for TS-resin transfer molding (RTM), used for non-automotive with future potential • BMW Landshunt plant in-house development of RTM and CFRP (M3 CSL CFRP roof) with 1500T press and automated part loading/unloading, in production • VW in-house development of CFRP, including A00 CFRP floor pan structure and 1litre/100km research car with CFRP structure, rear wheel arch in CF/APLC12, research projects • Renault – development of bladder-assisted RTM for automotive structures, research • TECABS CFRP RTM floorpan for VW lupo, FP5 research project • Menzolit netshape unidirectional SMC placement cell (advanced sheet molding compound (SMC) with VE resin), processed into hood structure, used by DC in SLR Mclaren, in production • EMS Chemie APLC12 process, RTM of PA12 into CFRP preforms, research stage • DaimlerChrysler – truck cab, suspension, in production • DaimlerChrysler/EPFL – integrated processing of polymers and composites (CF thermoplastic sheet stamping with over-injection molding), research stage with high-volume potential

Table 4.24: Summary of Comments about non-DOE CFRP Research	
Non-DOE CFRP Research in the U.S.	**Non-DOE CFRP Research Outside U.S.**
	• DaimlerChrysler – SLR Mclaren development, core cell of car and body panels from CFRP, variety of processes including carbon SMC and 2-D circular braiding with robotic arm for crush cones, in production • Fraunhofer ICT – development of reactive PA6 thermoplastic technology, research stage • EPFL/EMS Grivory – development of reactive PA12 thermoplastic technology, continuous sheet line development, TP-RTM development, demonstrated for an automotive floor pan quadrant, research stage • Dow Automotive – Cyclics program (reactive PBT system), claimed for RTM and sheet prepregging, with CF, research stage, no applications to date • Schappe Techniques CF/PA12 commingled yarn development, examined for truck braking system pressure vessels and automotive structures, mainly sport focused due to cost • Bond laminates CF/PA sheet prepregging (TEPEX), in production for non automotive with high volume production • Inoplast – RTM and SMC with carbon materials proposed for production solutions • Advanced composites group – CFRP prepreg stamping proposed for production solutions • Sotira, Airex – RTM of CFRP proposed for production solutions • HighTex 2D Tailored Fibre Placement Process using embroidery machinery

Table 4.25: Summary of Comments about Non-DOE Aluminum Research	
Non-DOE Aluminum Research in the U.S.	**Non-DOE Aluminum Research Outside U.S.**
Automotive Al research is very minimal reflecting the American trend of lower R&D expenditures. Most of the work is of the applied and material substitution nature. Areas being addressed include hydro forming, super plasticity, and friction-stir processing. Primary producers with U.S. facilities have partnered with automobile/light truck manufacturers to develop construction systems that enhance the use of aluminum in body structures (Alcoa and Alcan with Ford, GM, Daimler Chrysler and others). Products and technologies required are high-integrity die castings, extrusion stringers, cast nodes and auto-body sheet. Large number of projects undertaken by industrial consortia at WPI, Case-Western, Northern Iowa, Alabama and Georgia Tech for automotive castings. The same groups are active in supporting technologies, heat-treatment, joining, and new casting processes. Manufacturers of forming equipment are aggressively pursuing developments for aluminum. They include electromagnetic, explosive, hydraulic and pneumatic projects that are not being funded by DOE. Specific areas of development: • Thixomat used in magnesium casting remains under development for aluminum. • Alloy and composite developments are underway for rotors and drive shafts. • More formable 6xxx sheet alloys for closures. • Non-ludering 5xxx sheet alloys for body structures. • Forged steering knuckles • Welded tube for driveshafts • Large structural castings (over 50 lbs.)	The research is very active in Europe in the areas of product implementation, alloy development and application research. Japanese companies are beginning to be active in this area as they are far behind their North American and European counterparts. Alcoa and Alcan are active partners in aluminum-intense vehicle concepts at Porsche-Audi, Ferrari and Volvo. These programs are moving to fruition much more rapidly than similar U.S. programs. European auto makers seem to be more aggressive and risk-taking in seeking technologies, through their own means and through suppliers, for increasing fuel efficiency and performance by innovations in light-weighting. Japan is actively developing new casting processes for automotive components and is ahead of Europe and the U.S. in this field. Specific areas of development: • The scroll compressor for air conditioning. • Casting processes and alloys for diesel engine blocks. • Semi-solid suspension components. • 100% automated laser welding for partial and complete body structures. • Corrosion-resistant heat-treatable sheet alloys. Improved recovery during stamping.

Table 4.26: Summary of Comments about Non-DOE Magnesium Research	
Non-DOE Magnesium Research in the U.S.	**Non-DOE Magnesium Research Outside U.S.**
There are various oil pan projects ongoing at several OEMs. There is one oil pan in production at this time. Engine block activity at this time seems to be concentrated in Europe and there is at least one production project and at least one additional development project. Powertrain discussions always tend to leave out cam and valve covers. There are several development projects along with several production projects ongoing that are very relevant and could be commercialized. The biggest obstacle to commercialization is not lack of research or lack of funding. For the most part the DOE-funded magnesium R&D activities are right on the mark and are raising awareness of the real possibilities. There are two main reasons the rest of the world and in particular Europe is ahead of the U.S. The first is the presence of a real and compelling consumer force focused on performance and fuel economy. This is driven by the consumer and not legislation. The second is the dumping action in the U.S. It can be argued that the U.S. manufacturers that converted to magnesium had a technical edge over the rest of the world with the possible exception of Germany. Due to the dumping suit in particular and consumer preferences to a lesser extent, OEMs have moved their magnesium focus to Europe.	Because it is driven by real consumer needs (fuel cost) and real consumer wants (high performance) along with lower raw material cost (dumping suit), Europe will continue to outpace the U.S. in commercialization. Development of magnesium sheet technology is being done by Thyssenkgrupp and Frieburg University. The Austrian Research Centres are pursuing the development of formable magnesium alloys. Two organizations conducting research in this area in Canada are the Canadian Lightweight Materials Research Initiative (CLiMRI) and Auto 21 – Centers of Excellence, being comprised of Canadian universities. In China's Plan 863, magnesium is the major element in the Key Technologies research program. In Australia, CSIRO is conducting a sheet-metal-casting project, and CAST has a magnesium die-casting program.

Table 4.27: Summary of Comments about Non-DOE Lightweighting Steel Research	
Non-DOE Lightweighting Steel Research in the U.S.	**Non-DOE Lightweighting Steel Research Outside U.S.**
In the US, there is internal work going on at all the OEMs – Ford, General Motors, and DaimlerChrysler -- and steel producers – USS, Mittal, Stelco, Dofasco, Severstal, AK, and Nucor -- on AHSS. The internal R&D work seems to be focused on specific company related issues. These are typically near term projects that incorporate technologies into current designs and/or communicated in technical papers. The focus of this research effort is primarily on the development of enabling technologies for design, forming, and welding these advanced steels in normal auto-assembly processes. Only a limited amount of research is being done at Universities or Research Institutes on the subject of AHSS. Supplemental research on product characteristics is being conducted at US universities such as Colorado School of Mines. The work being funded by DOE through the USCAR is by far the largest activity. The application focus is largely aimed at reducing mass in the components involved in crash energy management or preventing intrusion into the passenger compartment where these materials offer the greatest benefit. Mass reduction targets are typically 25% for those components. The American Iron and Steel Institute conducts many studies to promote steel that are constructed to dovetail with the work being funded by the DOE and other research institutes. These are ongoing and relevant projects and include laser joining, laser-assisted joining, design methodologies, reparability issues, vehicle system cost studies, material characterization and failure mode analysis. There are also component-specific projects that develop applications using the advanced technology, such a steel wheels, steel fuel tanks, steel bumpers and steel welded products all being conducted with manufacturers of these components for the automotive industry. In addition, projects are conducted with individual OEMs on specific platforms to implement the most advance technology on vehicle designs in development today.	The International Iron And Steel Institute, AutoCo committee, represented by the majority of automotive steel suppliers around the globe. Past projects are ULSAB (Body-in-White), ULSAC (Closures), ULSAS (Suspension), ULSAB-AVC (entire vehicle design), which demonstrated the advantage of AHSS and these concepts are being incorporated in many vehicle designs today. Current projects by this organization are ongoing and relevant. These include Life Cycle Inventory of CO_2 competitive material in automotive design, high-strength steel stamping and joining guidelines, competitive material evaluations on specific design criteria. As in the U.S., individual steel companies are developing applications with OEMs, academia and other automotive suppliers that are often communicated in technical papers. Japan and Europe have largely solved the major implementation barriers to using advanced lightweighting steels in auto structures and their primary research emphasis is on developing enhanced versions of the existing advanced lightweighting steels, and on developing the next generation of advanced steels including twinning-induced plasticity steels and high aluminum-content austenitic steels with reduced density. The University of Stuttgart is doing some interesting die work that is going to be useful down the road.

Table 4.28: Market Penetration, Market Influences, and Threshold Gasoline Prices for CFRP Body Components							
Marketing Penetration (% sales)							
Estimate	**Pounds**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average	0-50	0.7	1.9	3.8	6.3	11.3	15.8
	51-200	0.3	0.7	1.4	2.7	5.9	11.5
	201-350	0.2	0.2	0.5	1.4	3.1	10.2
Low	0-50	0.4	1.3	3.0	5.2	8.8	12.2
	51-200	0.2	0.4	1.0	2.2	5.4	9.0
	201-350	0.1	0.1	0.3	1.2	2.6	8.4
High	0-50	1.0	2.6	4.6	7.3	13.8	19.4
	51-200	0.4	1.0	1.8	3.2	6.4	13.9
	201-350	0.2	0.2	0.6	1.6	3.6	12.0
Market Influences (%)							
Estimate	**World-wide R&D**	**DOE R&D**	**Renewable Resources**	**Low-Cost Fiber Develop-ment**	**Durability Composite Structures**	**Focal 3**	**Modeling Absorption**
Average	80.0	50.0	3.2	9.9	4.3	11.6	5.1
Low	74.2	43.0	5.0	8.3	3.3	10.2	4.2
High	85.8	57.0	7.6	11.4	5.3	13.0	6.2
Gasoline Price Threshold ($/gallon)							
Estimate		**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average		5.47	5.52	5.11	4.91	4.72	4.53
Low		4.94	5.00	4.56	4.38	4.19	4.00
High		6.00	6.06	5.65	5.48	5.25	5.06

Table 4.29: Market Penetration, Market Influences, and Threshold Gasoline Prices for CFRP Chassis Components							
Market Penetration (% sales)							
Estimate	**Pounds**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average	0-50	0.3	1.3	2.8	5.2	8.8	12.9
	51-200	0.3	0.4	1.1	2.6	4.4	7.3
	201-350	0.2	0.5	0.7	2.3	4.0	8.0
Low	0-50	0.2	0.8	2.1	4.0	7.2	10.0
	51 -200	0.2	0.2	0.8	2.0	4.2	8.0
	201-350	0.1	0.3	0.6	2.4	4.0	10.0
High	0-50	0.4	1.8	3.4	6.4	10.4	15.8
	51-200	0.4	0.6	1.4	2.6	4.6	6.5
	201-350	0.2	0.6	0.8	2.2	4.0	6.0
Market Influences (%)							
Estimate	**Worldwide R&D**	**DOE R&D**	**Renewable Resources**	**Low-Cost Fiber Development**	**Durability Composite Structures**	**Focal 3**	**Modeling Absorption**
Average	78.3	37.5	5.2	9.4	6.9	8.3	5.1
Low	72.5	31.7	4.3	8.4	5.5	7.0	3.8
High	84.2	43.3	6.1	10.4	8.3	9.7	6.5
Gasoline Price Threshold ($/gallon)							
Estimate		**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average		6.16	3.56	5.91	5.53	5.34	5.03
Low		5.44	5.56	5.19	4.93	4.69	4.31
High		6.88	7.13	6.63	6.13	6.00	5.75

Table 4.30: Market Penetration, Market Influences, and Threshold Gasoline Prices for CFRP Powertrain Components							
Market Penetration (% sales)							
Estimate	**Pounds**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average	0-30	1.4	2.0	3.3	6.5	7.4	9.4
	31-100	1.0	1.0	1.3	1.8	4.5	6.7
	101-200	0.3	0.6	0.6	1.0	4.9	10.1
Low	0-30	1.2	1.6	2.6	5.0	6.6	7.8
	31-100	0.8	0.8	1.0	1.6	3.8	5.2
	101-200	0.2	0.4	0.4	0.8	2.2	7.8
High	0-30	1.6	2.4	4.0	7.9	8.2	11.0
	31-100	1.2	1.2	1.6	2.0	5.2	8.1
	101-200	0.4	0.8	0.8	1.2	7.6	12.4
Market Influences (%)							
Estimate	**Worldwide R&D**	**DOE R&D**	**Renewable Resources**	**Low-Cost Fiber Develop**	**Durability Composite Structures**	**Focal 3**	**Modeling Absorption**
Average	69.6	33.5	5.4	7.7	9.0	5.7	3.8
Low	63.3	26.2	4.2	6.4	7.5	3.9	2.8
High	75.8	40.8	6.6	8.9	10.5	7.4	4.9
Gasoline Price Threshold ($/gallon)							
Estimate		**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average		6.91	7.16	6.53	6.03	5.72	5.53
Low		5.94	6.19	5.69	5.31	4.94	4.69
High		7.88	8.13	7.38	6.75	6.50	6.38

component area. Finally, the *durability of carbon-fiber composites* project is most influential in the powertrain area. The varying level of influence of the projects across component areas suggests that DOE has funded a diverse portfolio of projects.

As might be expected, the gasoline threshold price for CFRP body panels is the lowest of the three types of components and the threshold for the powertrain components is the highest. The threshold price declines over the years to reflect cost improvements in CFRP production technologies. In the longer-term, the gasoline threshold prices resemble current gasoline prices in Europe and Japan. A doubling or tripling of gasoline prices in the United States would be necessary to set the stage for a take-off in the United States. Current EIA oil price forecasts do not envision such price increases. However, several factors could come to pass in the future that could substantially increase gasoline prices to threshold levels for CFRP.

Tables 4.31, 4.32, and 4.33 contain the results from the other three Delphi exercises related to aluminum, magnesium and lightweighting steel, respectively. Table 4.31 suggests that aluminum will be found in much higher amounts than the other lightweighting materials addressed in this study. In the mid to longer term, most new light-duty vehicles will also contain a substantial amount of lightweighting steel. It is also anticipated that the amount of magnesium will increase significantly.

The DOE ALM effort is having a similar influence on the market penetration of aluminum, magnesium and lightweighting steel as in the CFRP area: DOE’s influence is rated in the 40 to

Table 4.31: Market Penetration, Market Influences, and Threshold Gasoline Prices for Aluminum Components							
Market Penetration (%)							
Estimate	**Pounds**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average	0-50	25.5	20.5	13.3	10.8	8.3	4.2
	51-200	38.7	41.2	41.7	38.3	35.8	35.0
	201-350	30.0	35.3	43.3	50.0	55.8	60.8
Low	0-50	28.3	21.0	15.0	13.3	11.7	8.3
	51-200	38.3	44.0	45.0	43.3	41.7	43.3
	201-350	26.7	30.0	36.7	41.7	46.7	48.3
High	0-50	22.7	20.0	11.7	8.3	5.0	0.0
	51-200	39.0	38.3	38.3	33.3	30.0	26.7
	201-350	33.3	41.7	50.0	58.3	65.0	73.3
Market Influences (%)							
Estimate	**Worldwide R&D**	**DOE R&D**	**Active Flexible Binder**				
Average	59.2	40.0	13.8				
Low	48.3	30.0	8.7				
High	70.0	50.0	19.0				
Gasoline Price Threshold ($/gallon)							
Estimate		**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average		3.38	3.79	4.20	5.24	6.96	8.94
Low		2.88	3.08	3.28	3.73	4.68	6.13
High		3.88	4.50	5.13	6.75	9.25	11.75

Table 4.32: Market Penetration, Market Influences, and Threshold Gasoline Prices for Magnesium Components							
Market Penetration (%)							
Estimate	**Pounds**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average	0-50	6.2	9.0	10.0	11.3	14.2	17.5
	51-200	3.8	6.0	7.5	7.8	9.7	12.5
	201-350	1.7	1.8	3.8	4.2	5.5	6.7
Low	0-50	4.0	6.3	7.0	8.7	10.	13.3
	51-200	2.0	4.0	6.0	6.3	7.3	10.0
	201-350	0.0	0.0	1.7	2.0	3.0	4.3
High	0-50	8.3	11.7	13.0	14.0	18.3	21.7
	51-200	5.7	8.0	9.0	9.3	12.0	15.0
	201-350	3.3	3.7	6.0	6.3	8.0	9.0
Market Influence (%)							
Estimate	**Worldwide R&D**	**DOE R&D**	**Mg Powertrain**	**Structural Cast**			
Average	58.3	42.5	20.3	8.0			
Low	50.0	36.7	15.7	6.7			
High	66.7	48.3	25.0	9.3			
Gasoline Price Threshold ($/gallon)							
Estimate		**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average		3.00	3.38	4.25	4.63	4.63	4.63
Low		2.75	3.00	3.75	4.00	4.00	4.00
High		3.25	3.75	4.75	5.25	5.25	5.25

Table 4.33: Market Penetration, Market Influences, and Threshold Gasoline Prices for Lightweighting Steel Components							
Marketing Penetration (%)							
Estimate	**Pounds**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average	0-30	5.6	3.8	0.0	0.0	0.0	0.0
	31-100	21.9	16.3	5.0	1.9	1.9	1.9
	101-200	5.4	28.8	45.0	48.1	48.1	48.1
Low	0-30	5.0	5.0	0.0	0.0	0.0	0.0
	31-100	22.5	20.0	8.8	2.5	2.5	2.5
	101-200	2.8	22.5	41.3	47.5	47.5	47.5
High	0-30	6.3	2.5	0.0	0.0	0.0	0.0
	31-100	21.5	12.5	1.3	1.3	1.3	1.3
	101-200	8.0	35.0	48.8	48.8	48.8	48.8
Marketing Influences (%)							
Estimate	**Worldwide R&D**	**DOE R&D**	**Auto /Steel Partnership**				
Average	97.5	45.0	23.3				
Low	95.0	36.7	18.3				
High	100.0	53.3	28.3				
Gasoline Price Threshold ($/gallon)							
Estimate		**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Average		-	-	-	-	-	-
Low		-	-	-	-	-	-
High		-	-	-	-	-	-

50% range. The research projects addressed by this study were also judged to have had significant influence in these market areas.

The Delphi panel experts suggest that gasoline prices will need to trend up in the future to help aluminum and magnesium products greatly increase their market penetration. The experts in the lightweighting steel area were in agreement that gasoline prices have no influence in the future market penetration of lightweighting steel components.

4.4.3 Energy, environmental, and security benefits

This section addresses the benefits attributable to the new vehicles projected to be on the road based on the analysis presented above. First to be considered are energy and environmental benefits. Energy benefits will accrue because the new vehicles will be lighter than today's vehicles. Reduced weight leads to reduced energy consumption, holding constant vehicle miles driven, driving styles, and road and weather conditions. The vehicle-use benefits estimation procedure takes into account the actual number of vehicles driven annually with different ages, assuming a vehicle life of 10 years and 10,000 miles driven annually. Environmental benefits will accrue during the use of these vehicles because for every gallon of gasoline saved there will be corresponding reductions in air pollution emissions, particularly carbon emissions. In this analysis, specific benefits assessed are gallons of gasoline saved and reductions in carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM_{10}), nitrogen oxides (NO_X), and sulfur oxides (SO_X) emissions. Environmental benefits considered at the use phase include both upstream benefits due to lower required fuel production and tailpipe emissions mainly restricted to carbon emissions. The correlation between improved fuel economy and reduced regulated criteria pollutant emissions appears unclear in today's literature. The tailpipe emissions are measured on a grams-per-mile basis and tailpipe criteria emissions are set irrespective of vehicle fuel economy, so it is argued that reduced criteria tailpipe emissions due to improved fuel economy may not be significant, or even existent.

Most reductions of environmental burdens are associated with the use phase of the automobile. To gain insights into other potential benefits of using new lightweighting materials in vehicles, it is useful to adopt a life-cycle view of automobiles and their components. Within the life-cycle framework, our analysis considers the extraction of raw materials from the earth, the processing of raw materials into refined forms, the manufacture of automobile parts and components from processed materials, and the recycling, reuse, or disposal of automobile parts and components of end-of-life vehicles. Environmental emissions and issues are associated with each of these phases, in addition to the vehicle-use phase addressed in the previous paragraph. Because it can be an enormous undertaking to track every material at every stage in the life cycle, this research focuses on only four of the five phases: extraction, materials processing, manufacturing, and use. These phases represent most of the environmental emissions associated with the automobile industry.

Thus, the life-cycle assessment task is centered on examining the environmental consequences of replacing steel components in vehicles with carbon-fiber-reinforced polymer composites resulting as the outcome of successful completion of DOE ALM R&D projects. Staff at the University of Tennessee's Center for Clean Products and Clean Technology (UTCPCT) provided estimates for the amounts of energy used and environmental pollutants emitted in producing one pound of steel, aluminum, and carbon-fiber polymer-composite material (Schexnayder et al. 2001). These numbers had been previously developed during other life-cycle assessment projects at the Center, including two projects supported by DOE and managed by ORNL related to the PNGV program. These numbers were translated into savings in energy use and environmental emissions per pound of new material used in the vehicles for an aggregate extraction, processing, and manufacturing stage, and for the use stage. These translated numbers are shown in Table 4.34. Life-cycle data for magnesium have been quite limited to date in the literature. Data at the extraction, processing, and manufacturing life-cycle stage are based on Hydro Magnesium (Hydro Magnesium, 2006) for the die casting of AZ 91 alloy with a 60% yield from the die-casting operation, whereas the use-stage data were derived using the UTCPCT data where a direct correlation between % part-weight-reduction potential with the lightweighting material use and % reduction in fuel use was found. Part-weight-reduction potential was assumed to be 50% for magnesium compared to 45% for aluminum. Due to lack of actual life cycle data, advanced high-strength steel data was based on assuming 25% part weight reduction potential using the UTCPCT conventional steel data and no significant changes in energy use in any of the manufacturing stages. It is anticipated that changes in life cycle energy use (if any) for advanced high-strength steel will be at the part manufacturing step (i.e., stamping vs. hydroforming), but even then the difference will not be that large to affect the outcome of the level of analysis considered here.

Table 4.34: Energy and Environmental Savings Per Pound of Material Used to Replace Steel								
Project Area Benefit Category	**High-strength steel**		**Aluminum**		**Magnesium**		**Carbon Fiber Polymer Composites**	
	EP&M[1]	**Use**	**EP&M**	**Use**	**EP&M**	**Use**	**EP&M**	**Use**
Energy (mmBtu)	0.0014	0.049	-0.0974	0.157	-0.0867	0.192	–0.0380	0.289
CO_2 (lbs)	0.6443	8.76	-9.3978	28.134	-12.9523	34.34	–2.2273	51.807
CO (lbs)	0.0004	0.025	-0.0614	0.081	-0.0108	0.100	–0.0016	0.150
PM_{10} (lbs)	0.0055	0.001	-0.0178	0.003	0.0317	0.004	0.0420	0.006
NO_X (lbs)	0.0011	0.005	-0.0414	0.015	-0.0037	0.019	–0.0367	0.029
SO_X (lbs)	0.0019	0.007	-0.0466	0.022	-0.0001	0.027	–0.0213	0.041
[1] Material extraction, processing, and part manufacturing								

Table 4.34 illustrates that the energy and environmental costs and benefits associated with new lightweighting materials for vehicles are variable across materials and benefit categories. Note that environmental benefits at the vehicle-use phase include both fuel production and vehicle use. As discussed above, criteria pollutant emission benefits at this phase include only fuel production. Generally, there are appreciable energy and environmental emission savings in the use phase, increasing in direct proportion with the weight reduction potential. However, with respect to the extraction, processing, and manufacturing phases, the picture is different. With the exception of high-strength steel, the remaining three lightweighting materials considered here require more energy to process than steel, resulting in more pollutant emissions with the exception of PM_{10} emissions in case of magnesium and carbon-fiber polymer composites. Note that for most cases of criteria air pollutants, there is a net increase rather than savings. There will be a substantial increase in CO_2 emissions particularly in case of magnesium resulting from casting operations.

In addition to understanding the magnitude of the energy and environmental impacts, we need to determine the monetary value of the impacts. In other words, what is the value of reducing fuel consumption by a gallon? Estimating these monetary values is a difficult and controversial exercise, one of the main criticisms of the use of benefit-cost analysis in the environmental field. Nevertheless, many attempts have been made to estimate these values. Riggert et al. (1999) have done a thorough job of reviewing the literature to distill the ranges in benefit estimates related to environmental emissions (see also NRC, 2001a).

DOE’s Energy Information Administration (EIA) publishes price forecasts for energy products (EIA, 2006). Using these sources, we developed three value scenarios, indicated in Table 4.37. The three value scenarios, i.e., base, moderate, and high correspond to low, average, and high, respectively, market penetration estimates obtained from the survey. Crude oil and gasoline prices were obtained from the EIA’s Annual Energy Outlook 2006 and three value scenarios correspond to low-price, reference, and high-price cases considered in that forecast (EIA, 2006). Values shown in Table 4.35 are based on the average value calculated using the price forecasts for the period 2005-2030, and original ’04 prices converted to ’05 prices by using consumer price index of energy commodities and services. For example, the value estimates for saving a gallon of gasoline range from a low of $2.06 per gallon to a high of $3.12 per gallon. The latest forecasts do consider the latest hike in the crude oil price but the high price case seems to be considerably higher than other available forecasts considered by EIA for comparison. On the other hand, gasoline prices seem to be on the conservative side considering the recent market price trend observed. Gasoline savings are associated with the vehicle-use phase whereas oil savings are associated with the extraction, processing, and manufacturing stage. Although coal, natural gas, and electricity are the most common energy types used at the extraction, processing, and manufacturing stage, oil represents the average energy value used in this analysis (i.e., $ per Btu).

Table 4.35: Energy and Environmental Emission Values Scenarios

	Base values case	Moderate values case	High values case
Oil ($/barrel)	44	60	90
Oil Security ($/barrel)	9	12	15
Gas ($/gallon)	2.06	2.43	3.12
CO_2 ($/ton)	7	27	55
CO ($/ton)	920	1000	1086
PM_{10} ($/ton)	40	1000	9953
NO_X ($/ton)	44	600	8143
SO_X($/ton)	110	200	2030

Assessing the value of the environmental benefits associated with the reduction of greenhouse gas (GHG) emissions and air pollutants is a difficult and controversial process. It is also an expensive process. This project did not have the resources to conduct original valuation research, so we turned to the existing literature. A particularly useful report was prepared for the State of Vermont to help it assess the benefits of its low-income home weatherization program (Riggert et al., 1999). Similar to lightweighting vehicles, making homes more energy efficient has the added benefits of reductions in greenhouse gas emissions and air pollutants. The authors of that report, also unable to conduct original valuation research, conducted an exhaustive review of the valuation literature to develop ranges of values associated with reductions in GHG emissions and air pollutants. We built our valuation estimates, in part, upon their work, knowing that it really does not matter from a valuation context how such reductions were accomplished. We also based our valuation estimates on the NRC (2001a) report evaluating DOE’s energy efficiency and fossil energy programs, which also based its estimates on a literature review.

As Table 4.35 suggests, the range in values is extreme for several of the environmental emissions. The base- and high-values cases represent the published ranges. The moderate case represents values that are more realistic than the low- and high-values cases. The range in valuation estimates is due to two main factors. First, different researchers use different methods. Thus, ranges are inevitable. Second, some valuation estimates focus on the market prices of tradable emissions permits whereas other estimates focus on human health benefits, reflected here in the high-values case, particularly for criteria air pollutants. In almost all cases, the market prices of tradable emission permits, which reflect the cost to industry to meet emissions targets, are much lower than the estimated social benefits of reduction of GHG and air pollutants. However, estimating social benefits is much more controversial and entails much more uncertainty than does estimating the value of emission permits. We have tried to find a compromise among the ranges of values and different perspectives within our adoption of mid-range valuation estimates.

The security benefit resulting from the prevention or mitigation of macroeconomic losses from energy disruptions has also been considered in the analysis here. The security benefit representing a reduction in the cost of an oil price shock is also shown in Table 4.38 in terms of $/barrel. A wide variation in the reported values of oil price shocks exists in the literature today. The base-value case assumes cartel pricing, whereas the high-value case is based on price shocks that have cost the U.S. economy during the past 28 years (Leiby et al., 1997). Since oil use occurs mainly at the use life-cycle stage, the security benefit is estimated only on that stage by converting total energy use into equivalent barrels of crude oil.

4.4.4 Market penetration benefit estimates

Tables 4.36 and 4.37 present the energy, environmental, and security net-present-value benefits (in 2005 dollars) attributable to the composite and non-composite projects, respectively, given the market penetration forecasts out to the year 2030, the values presented above, and a 7 percent discount rate, which is the current rate recommended by the Office of Management and Budget (OMB, 1996) for use in the benefit-cost analysis of regulatory actions required by the Executive Order. Benefits are presented for the three cases described above. As discussed before, the annual benefits are considered for the period 2007-2030, without consideration of the first two years of the benefits to correct for implementation costs of adopting the new technology. Environmental benefits include both carbon and criteria pollutant emissions as well, and the benefits due to carbon are also shown separately in this table.

As expected, the energy and environmental benefits for the extraction, processing, and manufacturing phases are negative in several instances. However, the use-phase benefits outweighed these negative benefits in most cases causing net positive benefits. Energy benefits are significantly higher than environmental and security benefits, although quite a controversy still exists over the value of the impacts in the latter case. Since net criteria pollutant benefits being positive (as shown in Table 4.36), total environmental benefits are higher than carbon emissions alone, particularly in the “High Values Case.” Although the estimated benefits of all DOE polymer composite projects appear to be significantly higher than five specific projects considered here, it is not the case when the sum of specific project benefits is considered. The sum of the five project benefits are estimated to be close to all DOE projects indicating that these five projects share the major overall DOE composite material portfolio. The low-cost fiber development program projects has the most benefits, whereas the modeling project being the least. The forecast period under consideration will affect the estimated benefits as more use-phase benefits are realized later in the forecast period with a greater number of lightweighting vehicles in the vehicle fleet.

Table 4.36: Energy, Environmental, and Security Benefit Results of Composite Projects (2005$ millions)				
Projects	**Energy**	**Environment***	**Security**	**Total**
BASE CASE				
DOE	$2347	$131 ($131)	$277	$2754
Focal Project 3	$551	$31 ($31)	$65	$647
Durability	$374	$21 ($21)	$44	$439
Renewable Fiber	$331	$18 ($18)	$39	$388
Fiber Development Program	$583	$33 ($32)	$69	$684
Modeling	$272	$15 ($15)	$32	$319
MODERATE VALUES CASE				
DOE	$3997	$612 ($589)	$541	$5419
Focal Project 3	$939	$144 ($138)	$127	$1210
Durability	$673	$103 ($99)	$91	$867
Renewable Fiber	$593	$91 ($87)	$80	$764
Fiber Development Program	$961	$147 ($141)	$130	$1238
Modeling	$509	$78 ($75)	$69	$655
HIGH VALUES CASE				
DOE	$6938	$1867 ($1574)	$934	$9740
Focal Project 3	$1631	$439 ($370)	$220	$2291
Durability	$1208	$325 ($274)	$162	$1696
Renewable Fiber	$1066	$287 ($242)	$144	$1497
Fiber Development Program	$1631	$439 ($370)	$220	$2290
Modeling	$936	$252 ($212)	$126	$1314
*Numbers inside parenthesis indicate environmental benefits due to carbon emissions only.				

Table 4.37 Energy, Environmental, and Security Benefit Results of Non-Composite Projects (2005$ millions)				
Projects	**Energy**	**Environment***	**Security**	**Total**
BASE CASE				
DOE (Aluminum)	$10,680	$341($364)	$2,982	$14,000
Flexible Binder Control	$3,456	$304($309)	$950	$4,710
DOE (Magnesium)	$1,308	$59($57)	$186	$1,553
MPCC	$559	$25($24)	$79	$664
SCMD	$238	$11($10)	$34	$282
DOE (High-strength steel)	$4,264	$241($236)	$445	$495
Lightweighting Front Structures	$2,138	$121($119)	$219	$2,477
MODERATE VALUES CASE				
DOE (Aluminum)	$16,720	$1,804 ($2,060)	$3,515	$22,040
Flexible Binder Control	$5,783	$624 ($712)	$1,216	$7,623
DOE (Magnesium)	$2,911	$341 ($303)	$524	$3,776
MPCC	$1,392	$163 ($145)	$251	$1,806
SCMD	$548	$64 ($57)	$99	$711
DOE (High-strength steel)	$6,752	$1,049 ($998)	$778	$8,578
Lightweighting Front Structures	$3,500	$544 ($518)	$403	$4,447
HIGH VALUES CASE				
DOE (Aluminum)	$26,140	$1,830($5,882)	$6,087	$34,060
Flexible Binder Control	$9,608	$619($2,167)	$2,276	$12,500
DOE (Magnesium)	$6,091	$1,675($1,066)	$1,086	$8,851
MPCC	$2,964	$836($501)	$562	$4,362
SCMD	$1,107	$312($187)	$210	$1,629
DOE (High-strength steel)	$11,070	$3,173($2,477)	$1,238	$15,480
Lightweighting Front Structures	$5,881	$1,686($1,316)	$670	$8,236
*Numbers inside parenthesis indicate environmental benefits due to carbon emissions only.				

As anticipated, the estimated benefits are maximum for aluminum under the non-composite projects considered here, followed by high-strength steel. The specific project, i.e., flexible binder control project, considered under aluminum is anticipated to contribute to 1/3rd of total energy benefits estimated for all DOE projects. The *lightweighting front structures* project is estimated to contribute significantly to the overall energy benefits in high-strength steel materials area. Although both *flexible binder control* and *lightweighting front structures* projects are estimated to cause similar level of market penetration of light-duty vehicles, higher weight-savings potential in the former causes higher overall energy benefits from increased fuel efficiency at the use phase. In case of magnesium, the SCMD project offers significantly lower benefits than the MPCC project.

4.4.5 Benefit-cost ratios

Table 4.38 contains social benefit-cost ratios for the projects. We calculated these by adding together the monetized energy, environmental, and security benefits and dividing by the project costs. Note that the security benefits considered in the benefit-cost ratios remain quite controversial in the literature today. The project costs indicated in Table 4.40 represent both DOE and private-sector contributions to the projects and include costs only through the fiscal year 2004, and not necessarily total in case of still incomplete projects. In every instance, the

Table 4.38: Benefit-cost Ratios				
Project	**Project Cost ($ millions)**	**B-C Ratio* Base Case**	**B-C Ratio* Moderate Case**	**B-C Ratio* High Case**
Composites				
DOE	66.4	41 (35)*	78 (60)*	147 (104)*
Focal Project 3	5.1	126 (108)*	236 (183)*	447 (318)*
Durability	7.2	61 (52)*	120 (93)*	235 (168)*
Renewable Fiber	3.1	124 (106)*	245 (190)*	479 (341)*
Fiber Development Program	3.6	188 (161)*	341 (265)*	631 (449)*
Modeling	4.4	73 (62)*	150 (117)*	301 (215)*
Non-composite projects				
DOE (Aluminum)	32.9	425 (324)*	669 (508)*	1034 (794)*
Flexible Binder Control	1.5	3217 (2360)*	5207 (3950)*	8540 (6563)*
DOE (Magnesium)	14.6	106 (90)*	259 (199)*	606 (417)*
MPCC	4.3	156 (131)*	424 (327)*	1023 (696)*
SCMD	8.2	34 (29)*	86 (67)*	198 (134)*
DOE (High-strength steel)	10.5	472 (407)*	818 (644)*	1476 (1056)*
Lightweighting Front Structures	3.1	804 (694)*	1443 (1136)*	2672 (1908)*
*Numbers inside parenthesis indicate benefit-cost ratios without taking into account environmental and security benefits.				

benefit-cost ratios are substantial. The benefit-cost ratios are significantly higher in the case of five specific composite projects compared to overall all DOE projects. A significantly lower cost on an individual project basis causes the ratios to be higher in the case of five specific projects. Secondly, benefits of five specific projects have been overestimated to some extent by the survey respondents since the sum of these benefits is very close to the benefits estimated for all DOE projects.

The ranking of five composite projects based on the benefit-cost ratios has somewhat changed from that on the estimated benefits shown earlier in Table 4.38. The fiber development project tops the list, whereas, a significantly higher project cost causes the durability project to be at the bottom of the list. Although the project costs are very similar in the case of two carbon-fiber related projects considered here, higher estimated benefits cause a significantly higher benefit-cost ratio in the case of the low-cost fiber-development project. Since the estimated environmental and security benefits are high, particularly under the high case, with the lower project cost the resulting benefit-cost ratios (which are also shown in this table) without consideration of these benefits are significantly lower than those when all benefits are included.

The estimated benefit-cost ratios of non-composite projects are significantly higher than for composite projects. The non-composite material areas, particularly the aluminum and high-strength steel areas, are comparatively more mature than the carbon-fiber polymer composite materials area. The selected projects under these two material areas are anticipated to aid in the significant penetration of these materials in light-duty vehicles, having significantly higher benefit-cost ratios than for overall material area. A significantly lower project cost in case of the *flexible binder control* project results in the most benefit-cost ratio in this case. The estimated benefit-cost ratios of magnesium are similar to carbon-fiber polymer composite projects, both indicating a relatively early stage of the use of these materials in light-duty vehicles.

4.4.6 Person-year and cost savings analysis

These benefits measure how many person-years and costs were saved by private-sector firms' participation in the R&D effort. Here we wish to measure the benefit (either financial or efficiency) from collaborating with DOE. The assumption is that private-sector firms enjoy some benefit from participating, even if there is a cost share. For the carbon-fiber composites evaluation, the inquiries posed to the key managers were

- would the company have participated without financial support from DOE,
- how many person-years would have been needed to achieve the same technical knowledge (response set of less than 1 year; 1-2 years; 3-5 years; more than 5),
- *cost savings* (with full benefits) realized by participating (response set: up to $100,000; $100,001 to $150,000; $150,001 to $200,000; more than $200,000)
- were their productivity or efficiency gains (and what percentage) (response set provided),
- what would the firm's commitment in staff and percentage effort have been if the company had engaged in this research without financial support from DOE (open-ended),
- an estimate of *person-years* it would have taken achieve the same technical knowledge the company now has (open-ended), and
- an estimate of the *total cost* to achieve the same technical knowledge the company now has.

The results for the carbon-fiber composites evaluation are presented in Table 4.39. To maintain confidentiality, a summation of responses is reported.

Table 4.39: Person-Year and Cost Savings				
	Composite-intensive body structure development for focal project 3	**Durability of carbon-fiber composites**	**Low-cost carbon fibers from renewable resources**	**Low-cost carbon-fiber development program**
Benefits Received from Participating in R&D Effort				
Person-years to achieve same technical knowledge	For university involvement in specific task: less than 1 year For other private-sector firms: (a) 3 to 5 years; (b) more than 5 years	Respondent 1: 1 to 2 years Respondent 2: more than 5 years	Less than 1 year	More than 5 years
Cost savings		Respondent 1: More than $200,000		More than $200,000
Productivity or efficiency gains		Respondent 1: Yes Respondent 2: Not sure		No[1]
Percentage of productivity or efficiency gain		1-15 percent		1 to 15 percent
Costs to Achieve Same Technical Knowledge				
Level of R&D effort without financial support from DOE			1 person in year 1, at average person year cost of $175,000, 25 percent effort; 2 persons each in years 2 and 3, at average person year cost of $175,000, 50 percent effort	Between 1 and 3 persons per year for a 4-year period at ranges of effort < 10% to around 60%
Person years to achieve same technical knowledge			1.25 years	Between 5 and 6
Total cost to achieve same technical knowledge			$220,000	$2-3 million[2]

(1). One respondent commented that there was an efficiency gain in terms of R&D knowledge and personnel experience.
(2). Because there was only one private-sector firm involved in the *low-cost carbon-fiber development* program, we did not sum the responses.

Revisions were made to this portion of the evaluation in the phase of this project that addressed non-composite materials. We kept the inquiry on whether their company or institution would have participated without federal support, and if the response was no, to reply on why.[50] We followed up with the investigators by asking them to complete a table on person-years committed by organization, project costs committed by organization, and year of introduction of product, with and without federal support. We then asked them to calculate the benefits from participating in R&D (difference between with and without federal support). To ensure confidentiality and because there were multiple firms involved in this effort, the person-years and total costs savings are presented in aggregate form.[51]

For the *active flexible binder control system for robust stamping* project, there were 10 person-years saved and $5,695,000 cost savings because of access to federal funding. Market introduction was reduced between four and five years.

The *lightweighting front structure* project had seven person-years savings and $2.2 million cost savings by having access to federal funding. Market introduction was reduced by six years. As noted earlier, the lightweighting material in this project is steel. Some could argue that the steel industry is a mature industry. When asked about the benefits of DOE's funding of this R&D effort, responses included:

- Funding critical for commercialization of affordable lightweighting materials. As a result of funding, AHSS will be accelerated into the marketplace in half the time it took high-strength steels, resulting in affordable fuel-efficient vehicles that fit into existing manufacturing and recycling infrastructure. Incorporation of AHSS will be in volumes sufficient to make a difference to the nation's energy consumption, without sacrificing vehicle safety or affordability.
- DOE funding allowed for quicker movement towards AHSS than if the auto industry solely funded the work. Collaboration that would not have naturally occurred resulted from the project. DOE involvement pushed the project to reach further than perhaps the Big Three would have pursued on its own.
- The project progressed the incorporation of AHSS technology to passenger cars due to the close collaboration between steel company representatives and original equipment manufacturers.

The *magnesium powertrain cast components* R&D project had 52.5 person-year savings and $27 million cost savings because of access to federal funding. Market introduction was reduced by

[50] The question regarding participation without DOE support was not posed to any U.S. national laboratory actively involved in these R&D projects. The term "counter-factual" is used to assess benefits to projects that would *have* proceeded in the absence of federal funding. As noted in our response sets, many of the companies would not have pursued this research without DOE participation (funding, availability of researchers at national laboratories, etc.). We present the person and cost savings as reported by the key managers, even if their company would have pursued the R&D without federal support.

[51] This is consistent with Link's methodology (1997). Responses are measured as the *difference* between "person-years committed by your organization" and "person-years needed by your organization to achieve same technical knowledge" and "project costs committed by your organization" and "total costs needed by your organization to achieve same technical knowledge."

between 2 and 16 years.[52] Written comments provided with the responses included (1) project probably would not have happened without DOE support and the project had added value by providing credibility and exposure of our firm to the original equipment manufacturers.

From the respondents in the *structural cast magnesium development* project, there were 21 plus person savings and $12 million cost savings by having access to federal funding. Market introduction was reduced between 3 and 10 years (using 2005 as a base year for the 2006 model year Corvette Z'06).[53]

4.4.7 Summary of economic analyses

In general, the benefit-cost ratios are positive for these R&D projects. Some are at the higher end of those reported by Link and Scott (1998) in their analysis of five Department of Commerce Advanced Technology Projects, which range from 4 to 85, and Martin, Gallager, and O'Connor (2000) for "Standard Reference Materials for Sulfur in Fossil Fuels," where the benefit-cost ration was 113. However, these ratios appear to be significantly lower than those reported by Chapman and Fuller (1996) for two National Institute of Standards and Technology programs, by Yuracko, Tonn, and Morris (1999) for several pollution projects funded by DOE at the Oak Ridge Reservation, and the three earlier ALM projects evaluated (Das et al., 2001 and 2002). Note that life-cycle impacts covering a relatively long forecast period of 25 years are considered in this study.

Although the private-sector firms do not always share the financial benefits they receive from participating in the R&D projects, those provided indicate that there were person-year savings and productivity gains.

[52] There were several key managers from the auto industry involved in this project. To avoid "double counting" we added the numbers provided by one representative of each auto company.
[53] We present "plus" because one respondent indicated the person-years and cost savings were innumerable.

5. CONCLUSIONS

The objectives of this evaluation were to assess short-run outputs and long-term outcomes that may be attributable to ALM R&D projects. Funded projects included in this evaluation range from applied materials science research to applied research in production environments. The R&D projects covered here also have the range of collaborators indicative of ALM projects: national laboratories, universities, original equipment manufacturers and their suppliers, and non-profit organizations. Four major lightweighting materials are reviewed in this evaluation: advanced high-strength steel, aluminum, carbon-fiber composites, and magnesium. Collectively, the nine projects selected are illustrative of major lightweighting materials research areas undertaken by ALM.

In addition to the feasibility and demonstration of different lightweighting materials technologies, the projects examine such issues as durability, cost, and safety, important for acceptability of any lightweighting material by the automobile industry. The projects also represent different levels of funding and project status (completed or on-going at the time of the data collection effort). Three projects have large budgets—the *focal project 3*, *magnesium powertrain cast components*, and *structural cast management development*. These projects are 100 percent cost-shared by the auto industry.

We selected four methods to evaluate the short-run outputs and long-term outcomes. We use multiple indicators for measuring each. The methods used are

- *Qualitative assessment.* We collected and assessed participant views about the benefits of the projects. Questions addressed whether the projects met their technical objectives; yielded knowledge; would have been conducted without federal support; enhanced collaboration among the participants; and produced results sufficient to make the lightweighting material a viable option for the auto industry. In the second set of evaluations, we added a question on whether the results would be incorporated into product design for light-duty vehicles, keeping in mind that several projects were on-going at the data-collection time. Answers to these questions indicated in most instances the immediate outputs of the R&D projects.

- *Indicators recommended by National Academy of Sciences' Committee on Science, Engineering, and Public Policy (COSEPUP)*. Participants' answers to prepared questions and a review of the projects' materials enumerated the number of publications and presentations associated with the projects, established whether the projects benefited from outside peer review, and whether the projects enhanced U.S. international competitiveness. These answers indicated both near (e.g., number of publications produced by the end of a project) and long-term benefits (knowledge level gained through the publications and increased international competitiveness of the Big Three automakers).

- *Quantitative benefits.* Researchers were asked to provide the number of undergraduate and graduate students supported each year on the project, whether patents and copyrights were applied for and received, whether software packages or project deliverables were developed and commercialized. If there were software packages, we asked if they had been distributed to the Big Three automakers, what was the reception, and equally important, whether the deliverable would be used in the decision-making process of the original equipment manufacturers in incorporating lightweighting material in production. This is both short-run outputs and long-term outcomes.

- *Economic analyses.* We conducted a benefit-cost analysis to monetize values for the benefits and costs of each project. While the benefits are due mainly to the commercialization of new technologies, companies also received benefits accruing from federal support. We developed forecasts to the year 2030 of market penetration of new vehicles benefiting from the new technologies. The benefits are estimated based on the projected market penetration of lightweighting materials in light-duty vehicles using a Delphi technique. Benefits examined include energy savings, reductions in air pollutants [e.g., carbon dioxide (CO_2), nitrogen oxides (NOx)], and security benefits. We assigned values to each benefit, and estimated benefits and costs. We defined costs as DOE support and private sector cost sharing. We calculated net present values for the benefits. We also calculated the ratio of benefits to costs for each project. In addition, we calculated monetized cost savings to industry by having access to federal R&D resources. In general, this is a long-term outcome because of the on-going nature of some of the projects and the time frame between completion of a project and introduction into the marketplace. The short-term nature is the cost savings accrued to industry by having access to federal R&D resources or DOE involvement in a material area.

We asked what other industries have or could benefit from the project. While direct attribution to ALM cannot be asserted, it should be of interest whether these projects could have other benefits. We also seek information on whether the project facilitated the private-sector firms involved in the research, either in facilitating introduction into the marketplace, competing in a broader market, etc.

In addition, we include an open-ended question that is particularly relevant to the evaluation. We asked each investigator to list what he or she viewed as barriers to wide-scale introduction of a specific lightweighting material. This is in addition to whether the project results were sufficient for a material to be a viable option, and in the aluminum, magnesium, and advanced high-strength steel projects whether the results would be incorporated by a company into product design for light-duty vehicles.

These broad methods were initially tested in two previous reports where the primary interest was on framework development and tested on a limited number of projects ALM funded in the mid- to late-990s (see Das et al., 2001 and 2002).[54] Where necessary, we expanded the methodology to better assess attributes of the R&D projects, specifically including a Delphi technique for the benefit-cost analysis. Moreover, these methods complement the benefits matrix developed for DOE's reports to Congress mandated under the Government Performance and Results Act of 1993 (GPRA). At this point, economic, environmental, and security benefits and costs are reported to Congress. Our framework also includes realized knowledge benefits and costs, yet to

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[54] The methods were subjected to numerous internal and external DOE peer reviews. In addition, two peer-reviewed publications resulted, where the appropriateness of the methods were scrutinized (Das et al., 2004; Peretz et al., 2005.)

be reported to Congress, through the qualitative assessment (knowledge gains); through the COSEPUP's coverage of publications and presentations; and through the quantitative assessment of patents, copyrights, software or other project deliverables, and graduate student support. All these are indicators of knowledge benefits.

The results from each lightweighting material covered in this evaluation are promising but there remains work to be done.

Carbon-fiber Polymer Composites
Although there may not have been unanimous agreement on qualitative components from the five carbon-fiber polymer composites projects considered under this lightweighting materials area, the indicators were positive in general. A majority felt that the technical objectives were met, the projects yielded knowledge, and collaboration was enhanced. It is clear that a majority of the private-sector firms, albeit the Big Three automakers or material suppliers, would not have engaged in carbon-fiber polymer composite research without funding from DOE. Similar success was observed when looking at the COSEPUP indicators. Each project supported a graduate student, even if a university was not an active member of the research team. Publications resulted from each project. None of the projects used an outside review panel as envisioned by the National Academy of Sciences, yet each benefited from peer review. Interestingly, in four of the five research projects, the investigators felt that the United States was leading in research in the use of carbon-fiber composites in product design for lightweighting vehicles. The results were less promising on commercialization, however. There, the majority felt that the United States was following or about even with other countries, primarily those in the European Union. Yet most felt that the research efforts will improve the U.S.'s international competitiveness in this field.

It should not be an expectation that each research project funded by DOE will result in a patent, copyright, or software development and commercialization. Regardless, in the projects that had software development or guidelines development as a primary goal—the *modeling of composite materials for energy absorption* and *durability of carbon-fiber composites*—the project delivery was well received by the OEMs and the research team expressed the opinion that the product would be used in the decision-making process for lightweighting automobiles.

Finally, the benefit-cost ratios are impressive. They range from 61 (*durability of carbon-fiber composites*) to 188 (*low-cost carbon-fiber development program*). While the results are less conclusive on the financial benefit from receiving federal support, there were still person-years savings from access to federal involvement (anywhere from 1 year for university engagement to more than 5 years from the private-sector engagement) and cost savings that accrued to the research partners.

The challenge for carbon-fiber polymer composites revealed through this evaluation is whether the material is a viable option for the OEMs. The results are not as irrefutable as those from other indicators included in this evaluation. In three of the five projects, a majority of investigators view the project results as sufficient to make carbon-fibers a viable option for the OEMs, but not for the remaining two projects. There was not a favorable majority view from the investigators engaged in the composite-intensive body structure for *focal project 3* (the largest project) and *durability of carbon-fiber composites*. In fact, the percentage of “no” or “not sure” responses was relatively high (86%) in the *durability of carbon-fiber composites*. One might assume that the results from the composite-intensive body structure for *focal project 3* reflect the on-going nature of the project. The durability project was closer to completion, however, at the time we collected data.

Across all five polymer composite projects, cost was the most frequently cited barrier to wide-scale introduction of carbon-fiber composite body structures in the manufacture of light-duty vehicles within the U.S. automotive industry. This was true even for the project that dealt specifically with cost. Other barriers were manufacturing/performance issues that remain unresolved, a perceived resistance to change or corporate culture of the OEMs in embracing a new material, and sufficient availability of carbon fibers. Other barriers mentioned less frequently were adequate materials property assessment of low-cost carbon fibers, market demand for lightweighting automobiles (or lack of demand), the fact that gasoline prices are still relatively low, and downstream conversion processes to deal with lost-cost carbon forms.

Of these barriers, some are obviously market-driven (demand, price of gasoline) and beyond the control of the research teams. Others deal with issues that are equally challenging to overcome: cost, manufacturing/performance issues, and corporate culture. Recall that respondents were commenting on their one project’s ability to affect the material’s introduction into vehicle design. They were not asked to consider the collective impact of ALM’s 23 polymer composites projects.

Aluminum
The *active flexible binder control system for robust stamping* project was demonstrated using aluminum as a lighter weight material. The managers included in this evaluation thought the objectives were met, knowledge was generated, and collaboration enhanced. As seen throughout most of the projects evaluated, the companies represented would not have participated in this type of research without DOE funding or involvement, or certainly not at the level of total funding. There were numerous publications and presentations. The researchers did not use a peer review panel, but received input from representatives of the auto companies, steel and aluminum companies, and university professors. The researchers did not believe the United States to be leading in research or commercialization in this field. However, there was 100 percent agreement that the results would improve the United States’ international competitiveness.

Graduate students were supported in each year of research effort. No patents or copyrights were applied for during the research period, although one respondent anticipates his firm will apply for two patents sometime in 2006. There were, however, four product deliverables from this R&D effort. The primary questions are (1) will the product be commercialized; (2) if so, when; (3) what was the reaction of the Big Three to the draft product, and (4) will the product be used by the Big Three in decision-making process on incorporating aluminum in production? Here the results are mixed. According to those participating in this evaluation, only one of the four products—control algorithm for non-linear systems—has the potential for commercialization, sometime in 2008. The results were favorable for this product, and a second deliverable—computer simulation/optimization codes. It is likely that the Big Three will use these two products in their decision-making.

The economic benefit of this research effort is remarkable. The benefit-cost ratio for this project is 3270, and there were 10 person-years and $5,695,000 saved by having access to federal funding. Market introduction would be reduced between four and five years.

The incorporation of the R&D project results into designs is questionable. We base this conclusion on those who responded “no” to the question, will results be incorporated into product design? We admit that 67 percent of the respondents indicated that the results were sufficient for the material to be a viable option for the auto industry, but when comparing those affirmative responses with whether the results would be incorporated into product design by that company, there was a negative response. In other words, a person might answer in the affirmative that the results were sufficient for the material to be a viable option, but negative to whether to the results will be incorporated into product design. However, there are positive actions in this R&D effort in that the Big Three will use results of two products in its decision-making process.

Barriers identified include cost, remaining manufacturing or performance issues, corporate culture, and low gasoline prices (an external factor). Cost and manufacturing or performance issues could be addressed in future research endeavors. Corporate culture might be tackled through further research convincing managers that this technology applied to aluminum is viable.

Advanced high-strength steel

The lightweighting front structure project focused on steel as a lightweighting material. The steel industry is a mature one. When asked about the benefits of DOE’s funding of this R&D effort, responses included that the use of high-strength steel would be accelerated into the marketplace—one assumption of DOE involvement—and the collaboration between steel companies and the original equipment manufacturers was enhanced.

There was unanimous agreement that the technical objectives were met, knowledge gains were achieved, and collaboration was enhanced. Interestingly, the majority of participants would have engaged in research without DOE funding. Although there were fewer publications and presentations, this appears to be a reflection of the number of researchers who served as key managers and participated in the evaluation. No outside panel was used, although the researchers benefited from reviews provided by the Joint Policy Board of the Auto/Steel Partnership, which included product and manufacturing staff from the three automakers, as well as comments provided by Auto/Steel Partnership experts outside the research project. The United States is not leading in research or commercialization in this field, but the majority of managers felt that the United States’ international competitiveness would be improved as a result.

There was graduate student involvement in the project. Although there were no patents or copyrights, one objective of the project was to develop a knowledge-based design tool. The tool has been distributed to the Big Three automakers, and the reaction was very favorable. With regard to specific reactions, one respondent noted that it was a useful tool that will aid in design of experimental exercises; another participant felt that the Big Three were interested in the methodology of the tool. Two of the investigators indicated that the Big Three would use the tool; one pointed to manufacturing body structures, in model year 2006 and beyond.

There is agreement that the results of the project would be incorporated into product design for light-duty vehicles and that the results were sufficient for steel to be a viable option for the OEMs. Regardless, barriers still exist: manufacturing/performance issues, infrastructure demands, and quality/safety standards.

Magnesium

The final lightweighting material included in this evaluation is magnesium. Two magnesium projects were evaluated: *magnesium powertrain cast components* and *structural cast magnesium development*. These two research efforts were the largest two evaluated, in terms of research team members who played a key role and those who responded.

For magnesium, there were conflicting results on whether technical objectives had been met, but this divergence appears to be a function of the status of the project, i.e., completed or still in progress. In the *magnesium powertrain cast components* project, only 55 percent agreed that the project had met the technical objectives. However, 31 percent of those responding "not sure," qualified their responses with comments such as they were engaged in only one task and did not feel comfortable speaking for the broader project, or the project was still on-going so such assessment was premature. The majority felt that the effort had yielded knowledge.

There was near unanimous agreement that the *structural cast magnesium development* project met its goals (90 percent), and 100 percent felt the project yielded knowledge. The majority in both projects would not have participated in research without DOE funding or involvement in the magnesium field. Collaboration was enhanced in both cases as measured through their willingness to engage in future research endeavors.

With projects involving so many persons, a number of publications and presentations would be expected and that is the case with both of these projects. Neither project had a peer-review process as envisioned by COSEPUP; however, as with the other projects, the project profited from oversight from several sources.

The *magnesium powertrain cast components* R&D project was organized initially with seven steering committees, staffed with experts from industry, universities, and research laboratories, to provide a review and approve next steps in the research effort. One key manager noted that the testing firms used were accredited and worked independently. Another commented on review by experts affiliated with the Big Three automakers, but not serving on the research effort. In addition, there were annual reviews by USAMP's Advanced Metals Division (AMD). One investigator noted that conference presentations were reviewed. Several researchers mentioned that their work was reviewed by the core team or suppliers for the auto industry. Another mentioned DOE review.

The *structural cast magnesium development* team held quarterly and yearly meetings with steering committees and DOE representatives; members of the supply chain provided in-kind review; one respondent had a company representative knowledgeable in the field but not directly involved in the R&D effort provide a review. There was review by the Industry and Government Steering Committees for the Canadian Lightweighting Materials Research Initiative.

Project members' assessment is that the United States is not leading in research or commercialization of magnesium. But the investigators felt that the projects will be an improvement in the U.S.'s international competitiveness.

There were a large number of bachelor, master's, and doctoral students involved in the magnesium projects. One patent was applied for in 2005 from the *magnesium powertrain cast components* research. Several respondents anticipate their firms applying for patents and copyrights in the *magnesium powertrain cast components* research effort. Patents are expected from the *structural cast magnesium development* effort as well.

There were many products that were developed in these projects; some with commercialization possibilities, others not. It appears at this point that the following products from the *magnesium powertrain cast components* have potential for commercialization: alloy testing, selection, and database; coolant-corrosion investigation/evaluation; some components of the current and future research for North America; component filling and solidification models; component tooling; excised specimen testing; and engine durability testing. Considering that the project is on-going, it is not surprising that anticipated dates of commercialization range from 2006 to 2008 at the earliest. The reaction of the Big Three to the deliverables has been favorable or very favorable in most cases. In addition, for each deliverable there were positive responses that the product would be used by the OEMs in their decision-making process for incorporating magnesium into automotive production.

From the *structural cast magnesium development* R&D effort, there is potential for commercialization for the magnesium alloy database; radioscopic standard for magnesium castings; and failure model. Dates range from 2006 to 2010. All the products were favorably or very favorably received. Moreover, the respondents indicated that the products would be used by the Big Three in decision making beyond General Motors' 2006 Corvette Z'06.

The benefit-cost numbers are positive for both magnesium projects. Furthermore, there were substantial person-year savings from these projects: 52.5 years from the *magnesium powertrain cast components* and 21 years from the *structural cast magnesium development*. Similar cost savings were observed: $27 million and $12 million, respectively. Market introduction was reduced between 2 and 16 years for the *magnesium powertrain cast components* and between 3 and 10 years for the *structural cast magnesium development*.

The question remains, however, on whether the results will be incorporated into product design for light-duty vehicles and whether the results are sufficient for magnesium to be a viable option. In the *magnesium powertrain cast components* endeavor, 68 percent believed the results would not be incorporated or were uncertain about it. Slightly more than a half (55 percent) felt that the results were sufficient for magnesium to be a viable option. These responses may be explained by the fact that the project is on-going.

Slightly more than a half of those participating in the *structural cast magnesium development* evaluation believed that the results would be incorporated into product design and that the results were sufficient for the material to be a viable option. The results were lower than expected considering that General Motors uses a magnesium engine cradle.

Not surprisingly, barriers were cited from the participants in this group. Nineteen of the 20 respondents from the *structural cast magnesium development* project and 25 of the 29 from the *magnesium powertrain cast components* cited barriers to widescale introduction of magnesium in the manufacture of light-duty vehicles. Obstacles include cost, manufacturing/performance issues, corporate culture/resistance to change, infrastructure demands, quality, safety standards, corrosion, international tariff policies, competing technologies and materials, acceptance by the engineering community.

As noted at the beginning, there are two perspectives that can be taken from this evaluation. When considering an overwhelming majority of the indicators selected, the responses are outstanding. Despite the fact that there are still questions on whether the results will be incorporated or whether a material is a viable option returns to the fundamental issue of DOE involvement and collaboration with the automobile industry. What this evaluation has highlighted is the on-going challenges to change in the automobile industry

Moving to lightweighting materials must overcome at least two serious “catch-22s.” First, it must be understood that OEMs are not material producers but parts consumers. OEMs may not demand lightweighting parts until they can be proven to be cost competitive, reliable, and amenable to mass manufacture. On the other hand, suppliers may not invest in the R&D for lightweighting parts until the OEM's begin to demand parts made from lightweighting materials. A second “catch-22” involves lack of expertise in lightweighting materials in both OEM and supplier organizations. Again, neither may have incentive to develop such expertise until it can be shown that such expertise is needed. But, the expertise itself is needed to understand the potentials and limitations of the new materials. These catch-22s make it difficult for the industry as a whole to move to new materials as quickly as would be necessary to achieve overall energy, environmental, and security benefits for the public.

The ALM effort helps to reduce the risks to the OEM’s and suppliers from exploring new materials. The program also facilitates discussion and collaborations amongst the OEMs and suppliers to help overcome the catch-22s described above. The program is valuable in helping to identify next steps to developing new lightweighting parts. The ALM effort brings expertise in the materials found in national laboratories and universities that can get the discussions and R&D moving. It has also been shown that the projects help to build the necessary “critical mass” of professional expertise needed to move the industry forward in these materials areas. This expertise could then direct future R&D in many new directions, not only in the directions represented by the ALM-funded projects.

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APPENDIX A

Methods for Conducting Program Evaluations

1. Economics. In addition to the traditional benefit-cost ratios, a more recently used economic measure gauges how much private sector investment is needed to achieve a certain level of technical capability. It seeks a response to "In the absence of . . . [federal funding] . . . , what would your company have had to do to obtain the same level of technical capability that it currently has, and what resources over what time period would have been needed to pursue such an alternative" (Link and Scott, 1998, page 14).

For more on the use of economic methods for evaluating federal R&D and weaknesses as a methodology, see NAS, 1999; U.S. GAO, 1997; Link, 1993; Rouse, Boff and Thomas, 1997; Brown, 1998**.**

2. Bibliometrics. The use of bibliometrics has been accepted as a proxy for R&D benefits because of the difficulties in evaluating R&D activities (Melkers, 1993). Bibliometrics can serve as a source of information on "measurement of scientific output, the extent of knowledge transfer and the impact of research, and an approximation of the links between science and technology" (Melkers, 1993, page 49). Its use has been expedited by the creation of the Science Citation index.

These metrics serve as a quantitative, well understood proxy for how the research is viewed. Use of bibliometrics is based on the assumption that a researcher's work is valuable when judged so by a researcher's peers. Acceptance of a peer-reviewed paper occurs after a traditionally rigorous evaluation process of its merit. Citation counts can appear in patent applications, as well as other research in the field. Patents can show a nation's technological strength and are a signal of innovation from an R&D project. Brown (1998) reports a strong relationship between scientific papers cited on patent applications and federally funded R&D.

3. Case studies. Case studies clearly identify qualitative issues, such as degree of collaboration, training for junior researchers, and the dynamics within a specific setting that can be used to judge success. A commonly cited justification for using case studies as a research method is due to a lack of clearly understood theory to associate with results. Specifically, for R&D, the uncertainty lies in how different types of R&D projects affect economic growth (Yin, 1984; Kingsley, 1993).Case studies of federal R&D and economic growth became popular in the 1960s. Case studies can be expensive to conduct, a clear limitation to their extended use.

4. Peer reviews. Peer review is a self-evaluation in the sense that reviewers come from the researcher's primary disciplinary field. Its premise is that those most knowledgeable in the field can gauge research agendas and the qualifications of those conducting the research. Who is defined as an expert can raise questions about bias and favoritism. For example, the Committee on Science Engineering, and Public Policy (COSEPUP) of the National Research Council was asked to review how federal agencies should respond to GPRA's performance requirements on R&D projects. COSEPUP's report, which emphatically recommends the use of peer review (or expert review) when evaluating government R&D programs, noted that "legitimate concerns ... have been raised about expert review (such as conflict of interest, independence, and elitism)" (NAS, 1999, pages 32-33).

APPENDIX B

Benefits Matrix for the PNGV Program[a]

	Realized Benefits/Costs	Options Benefits/Costs	Knowledge Benefits/Costs
Economic benefits/costs	DOE cost (1995-1999) approximately $371 million. Total federal funding approximately $1.3 billion. Industry cost share: substantial but indeterminate. Lightweighting materials are generally more expensive than steel, giving negative economic benefits. However, improved manufacturing processes, fuel savings, and reduction in subcomponents can sometimes compensate for higher material costs. (For example, the Chevrolet pickup bed has a positive economic benefit, as much as 2%, if compared with steel at annual volumes less than 75,000, but a negative benefit at higher volumes due to tooling replacement. Customer saves about $12 in fuel cost per year. Benefit is positive if compared with a composite aftermarket liner.) Some manufacturing technologies in use have positive economic benefits (e.g., welding, forming, drilling, springback). Lightweighting materials: (a) aluminum (b) magnesium (c) composites (1) Chevrolet Pickup Bed (2) Jeep Hardtop	When eventually applied, option economic benefits will be positive for the following: (1) Improved body structure (2) Design (3) Manufacturing technologies: (a) casting, (b) painting, (c) ion-implantation, (d) induction heating, (e) adhesive bonding (4) Rapid prototyping (5) Combustion diagnostics (6) Phosphor thermometry (7) Simulation/modeling (8) Virtual reality (9) Recycling Because they appear to be more expensive than the corresponding conventional technologies they replace, when and if eventually applied to automobiles, option economic benefits may be negative for the following: (1) Hybrid power train (2) High-power batteries[b] (3) Materials (a) Ni-aluminide dies(b) diamond-like coatings (4) Lightweighting airbag (5) Hybrid power train technology (6) High-power batteries[b] (7) Materials (a) Ni-aluminide dies (b) diamond-like coatings (8) Lightweighting airbag	Gaining knowledge collaboratively reduces duplication of effort and corresponding cost Recycling Gas turbines/ceramics Fuel cells[b] Fuel reformers Stirling engines[b] Exhaust catalysts[b] (A) plasma treated (b) vacuum insulated (c) lean burn Lightweighting engines Alternative fuels High-power energy storage (a) highpower batteries[b] (b) ultracapacitors (c) flywheels (d) pneumatic/hydraulic Power electronics Diesel injection pump Diesel emission control Modified diesel fuel Variable compression ratio engine Air conditioners Lightweighting interiors Aerodynamic drag

	Realized Benefits/Costs	Options Benefits/Costs	Knowledge Benefits/Costs
Environmental benefits/costs	Reduced weight gives improvement in fuel economy and reduced CO_2 emission. Pickup bed gives 1.3% vehicle weight reduction, or 0.18 mpg fuel economy improvements.	Reduced weight and more efficient vehicle gives improvement in fuel economy and reduced CO_2 emissions	Reduced weight and more efficient vehicle that meets emission requirements gives improvement in fuel economy and reduced CO_2 emissions.
Security benefits/costs	Same as environmental Improved fuel economy reduces demand for imported oil.	Same as environmental Improved fuel economy reduces demand for imported oil.	Same as environmental Improved fuel economy reduces demand for imported oil. Knowledge applicable to military use.

[a] Unless otherwise noted, all dollar estimates are given in constant 1999 dollars through 2000.
[b] Separate cases for this technology were conducted by NAS (2001)
Source: NRC, 2001a, Appendix E, page 148.