Application of Lightweighting Technology to Military Vehicles, Vessels, and Aircraft

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APPLICATION OF LIGHTWEIGHTING TECHNOLOGY TO MILITARY AIRCRAFT, VESSELS, AND VEHICLES

Committee on Benchmarking the Technology and Application of Lightweighting

National Materials and Manufacturing Board

Division on Engineering and Physical Sciences

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Preface

Lightweighting is a concept well known to structural designers and engineers in applications from laptops to bicycles to automobiles to buildings and airplanes. Reducing the weight of structures can provide many advantages, including increased energy efficiency, better design, improved usability, and better coupling with new, multifunctional features. At the same time, the methods needed to achieve implementation of lightweighting are not well understood. And although lightweighting is a challenge in commercial structures, the special demands of military vehicles significantly stress the already complex process.

It is in this context that the U.S. Department of Defense (DoD), through Reliance 21,[1] requested that the National Research Council (NRC) conduct a study, under the auspices of the National Materials and Manufacturing Board, to assess the current state of lightweighting implementation in air, sea, and land vehicles and recommend ways to improve the use of lightweight materials and lightweighting solutions. Appointed by the NRC, the Committee on Benchmarking the Technology and Application of Lightweighting comprised members chosen for their expertise in materials (including ceramics, polymers, metals, and composites); use of materials in air, sea, and land transport vehicles; systems engineering; and technology assessment, economics, and transfer. Short biographies of the committee members are provided in Appendix A. The committee's statement of task is given in Chapter 1, along with the committee's interpretation of its task and a description of how it carried out its work.

The committee's work was aided greatly by a number of people, including the DoD's Reliance 21 Materials and Processing Team and the experts who took the time to speak to the committee: Bruno Barthelemy, Gene Camponeschi, Julie Christodoulou, John Deloach, Lisa Prokurat Franks, John Gill, Roger Halle, Robert Hathaway, Charles Kuehmann, James Malas, Suveen Mathaudhu, Mark Middione, Jim Ogonowski, Robert Rapson, and Robert Sielski. Appendix B lists the presentations made to the committee.

My personal thanks go to the entire complement of committee members for their outstanding expertise, limitless enthusiasm, and dedicated efforts in discussing the vast amount of information on lightweighting that we received and in writing the report. I am particularly grateful to Frank Zok and Brad Cowles for their exceptional dedication and vision at key points in the process. They served as unofficial committee co-chairs, providing leadership to see the report through to the final version. We are all grateful to Madeline Woodruff, a senior program officer in the NRC's Division on Engineering and Physical Sciences, who served tirelessly as study director and assisted

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[1] Reliance 21 is a management process developed by the Director of Defense Research and Engineering (DDR&E) that involves the science and technology (S&T) executives of all the military components under the aegis of the DDR&E. All the DoD and military service S&T organizations prepare biennial S&T strategic plans that are informed by and harmonized with an overarching DoD S&T strategic plan.

the committee in the preparation of its report under the direction of Dennis Chamot, acting director, National Materials and Manufacturing Board. The study benefited greatly from the work and advice of Janice Mehler, associate executive director, Report Review Committee. Special appreciation is expressed to Daniel Talmage, who helped with the preparation of the report during the final stage of the project, and to Laura Toth and Ricky D. Washington for assistance with meeting arrangements and communications with the committee.

L. Catherine Brinson, *Chair*
Committee on Benchmarking the Technology
and Application of Lightweighting

Acknowledgment of Reviewers

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

Thanks go to the following individuals for their participation in the review of this report:

William F. Baker (NAE), Skidmore, Owings & Merrill,
Jay Baron, Center for Automotive Research,
Charles N. Calvano, U.S. Naval Postgraduate School,
W. Peter Cherry (NAE), Independent Consultant,
Donald U. Gubser, Naval Research Laboratory,
Elizabeth A. Holm, Sandia National Laboratories,
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Mark Schaeffer, Mantech SRS,
Robert E. Schafrik, GE Aircraft Engines,
Haydn Wadley, University of Virginia, and
Ben Wang, Florida State University.

Although these reviewers provided many constructive comments and suggestions, they were not asked to endorse the committee's findings or recommendations, nor did they see the final draft of the report before its release. The review was overseen by R. Steven Berry, University of Chicago. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and institution.

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Summary

Reducing the weight of military vehicles has been of interest to the U.S. Department of Defense for decades. For land vehicles, the objectives historically have been primarily to reduce fuel consumption and costs and improve transportability. For naval vessels, lightweighting of superstructures also improves balance, maneuverability, and speed. For aircraft, weight is a critical determinant of performance, payload capacity, maneuverability, and range.

Reducing vehicle weight without compromising other important attributes such as survivability or payload capacity has traditionally been accomplished through the substitution of lightweight materials for heavier ones within conventional design configurations. However, this narrow perspective limits the possibilities for and the impact of lightweighting.

Today, in the face of new and evolving threats, improving the survivability of a military vehicle and its occupants has become more important than reducing fuel use. However, as has been seen in recent years in the deployment of land vehicles in Iraq and Afghanistan, the need to counter new threats has sometimes compromised other performance capabilities. For instance, the need to “uparmor” some vehicles to increase survivability has, by increasing their weight, reduced their maneuverability and transportability and increased their fuel requirements. Lightweighting can now be viewed as a means of restoring or even improving such vehicles’ maneuverability and transportability and reducing their fuel consumption.

To help it take fuller advantage of the benefits of lightweighting, the Department of Defense (DoD) asked the National Research Council (NRC) to assess the current state of lightweighting in land, maritime, and air vehicles and to recommend ways in which the use of lightweighting might be better implemented in military vehicles, but also to address commercial vehicles.

As part of its assessment, the Committee on Benchmarking the Technology and Application of Lightweighting was asked to consider both lightweight materials and lightweight design; the availability of lightweight materials from domestic manufacturers; and the performance of lightweight materials and their manufacturing technologies. (Manufacturing technologies are those used to manufacture materials as well as the components, structures, and other shapes made from the materials.) It was also asked to consider the “trade space”—that is, the effect that use of lightweight materials or technologies can have on the performance and function of all vehicle systems and components.

The committee began by assessing the relevance of the definition of lightweighting in the materials community. Particularly mindful of the need to consider lightweighting and the trade-space of vehicle attributes holistically, the committee developed the following broad definition of lightweighting in military systems:[1] Lightweighting is the process of reducing the weight of a product, component, or system for the purpose of enhancing certain attributes, notably (1) performance, (2) operational supportability, and (3) survivability.

In developing this broad definition, the committee wished to emphasize that lightweighting should be viewed as a means of achieving a variety of desirable features:

- Improved fuel economy that would reduce both fuel expenditures and the logistical support needed to supply fuel to forces deployed in remote and hostile locations;
- Better performance in the form of, for example, increased speed, mobility, maneuverability, range, and payload capacity;
- Better operational supportability in the form of, for example, better transportability, durability, repairability, and maintainability; and
- Improved survivability.

Lightweighting is critical to optimizing vehicle performance and capability and to reducing fuel use and costs. Lightweighting can also confer the benefit of flexibility and adaptability. For example, a vehicle that can be made lighter without compromising survivability provides the flexibility to add new capability—e.g., to add armor in a modular fashion or to add payload—without increasing weight beyond the original weight or even while maintaining an overall lighter vehicle. In general, vehicles can be adapted for different uses, such as responding to evolving threats.

Lightweighting encompasses the design, development, and implementation of lightweight materials, components, and other technologies as well as the capability to manufacture and produce such materials and components at reasonable cost.

Under the committee's broad definition, lightweighting demands a true systems approach. A focus on only one vehicle attribute may result in a weight reduction but may miss the more significant benefits that could be attained through a more systematic consideration of lightweighting throughout a vehicle system's design cycle. Lightweighting must be done at the systems level to ensure proper balance with all other critical requirements. Use of advanced, lightweight materials, and optimization of all materials and structural configurations at the systems level, are key to achieving optimal systems performance and the lightest weight.

A systems approach to design might consider not only the development and use of lighter (low-density) and high-specific-performance[2] materials, but also:

- Creative architectural and component designs that provide multifunctionality;
- Manufacturing methods that enable the use of new designs and material combinations as well as the reduction of manufacturing defects (thus improving durability and service life);
- Research to improve understanding of materials' response and failure mechanisms; and
- Enhancement and broader use of computational models that can accelerate the materials development and qualification cycle through integrated computational materials engineering.

The committee addressed its charge by reviewing illustrative examples of lightweighting in air, sea, and land vehicles, with a focus on military applications. It also considered some of the opportunities available to implement lightweight solutions. Although not definitive, the review found good examples of lightweighting implementation in military vehicles, but there is still much that can be done. Viewing lightweighting broadly, as defined by the committee, and at the systems level may help bring opportunities to light.

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[1] Although this definition also applies to civilian vehicles, the main focus of the report is military vehicles, and so the attributes of interest and the wording used are tailored for military applications.

[2] For example, high specific strength, which is defined as strength divided by density.

The committee also identified barriers to further lightweighting, one of the most important of which involves the extended period required for materials development and qualification. "Gated" processes for developing new products or systems, such as those specified by the Defense Acquisition Guide and DoD Instruction 5000.02, require that technologies be relatively mature by the initiation of a program. Hence, the considerable time and cost required to reach the requisite level of maturity for a new material must be expended in the preacquisition phase, before a program is actually initiated. As a result, the development and qualification cycle for materials is often "out of sync" with the design cycle for vehicles, making it difficult to insert new materials early in the design cycle.

A second barrier to lightweighting is that the use of advanced materials, such as magnesium and titanium alloys and polymer matrix composites, can be hampered by high costs, manufacturing challenges, and the lack of domestic, commercially available supplies. It can even be difficult to obtain high-strength steels, which, when combined with manufacturing innovations, can contribute to reducing weight and enhancing performance.

Another important obstacle is that neither the specification of technical requirements for contractors nor the acquisition process for new vehicles and equipment promotes innovation. Detailed specifications offer no flexibility to meet performance requirements in creative ways. When several contractors are involved in the development of a vehicle or system, poor communication can result in less than optimal solutions. Moreover, development and acquisition programs for vehicles are often risk-averse, resulting in the exclusion of new technologies and materials that could contribute to lightweighting. Under these conditions, implementation of a systems approach can be severely impeded.

The committee developed the following findings and recommendations on approaches to better implement lightweighting solutions in aircraft, maritime vessels, and land vehicles.

DIGITAL DESIGN TOOLS FOR SYSTEMS ENGINEERING

Finding 1: One consequence of lengthy acquisition processes is that changes in threats and operational requirements in areas of conflict can outpace development of new military vehicles and vehicle technologies. The ability to keep up with evolving requirements could be improved by both reducing the time required for development and improving the capability to design flexibility and adaptability into vehicle systems. Both goals require increased capability in digital design, especially for the integration of materials and design configurations. Such capability could significantly improve the effectiveness of current systems engineering processes.

Recommendation 1:[3] The DoD should initiate a program to develop and integrate high-fidelity models of materials, processes, and performance into a comprehensive digital system-design process for future air, maritime, and land vehicles. Although many individual models exist or are being developed, these models often are not integrated, and the focus of a larger organization such as the DoD is required to facilitate coordination.

Finding 2: In addition to the models themselves, a framework for their effective integration into the vehicle design environment is required. An important element of this framework is integrated computational materials engineering (ICME), a strategy that extends from materials design through structural design in an integrated fashion, thereby including the ability to design new materials as part of achieving optimal structural performance. In the committee's judgment, ICME tools and methods offer the greatest opportunity to accelerate the development and validation of new materials and processes for lightweighting, which would bring the current lengthy development cycle for these new materials and processes more into line with the generally much shorter design cycles for vehicles and products. Although numerous programs and specific applications have demonstrated the feasibility and benefits of ICME, broad development and implementation will require comprehensive, sustained effort and investment, along with coordinated actions among numerous stakeholders, to have a significant effect on future components, vehicles, and systems.

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[3] During the course of this study, the Obama Administration announced the new Materials Genome Initiative, which addresses many of these needs. See Chapter 6, Box 6-1.

Recommendation 2a:[4] The DoD should expand its leadership role as a champion of integrated computational materials engineering. It should develop and lead a comprehensive, sustained, multi-agency ICME program, with some specific focus on lightweighting materials and technologies. The program should:

- Identify and support foundational engineering problems[5] that specifically address lightweighting for air, maritime, and land applications;
- Foster the development and stewardship of national curated knowledge repositories relevant to lightweighting materials;
- Coordinate with other stakeholders in the training and education of an ICME workforce; and
- Support the development of a suite of predictive tools for materials manufacturing, sustainment, and maintenance. These should address processes, performance, and properties and should include physics-based materials models of behavior under extreme loading conditions.

Recommendation 2b:[6] The DoD should foster the development, maturation, and advancement of physics-based materials models as well as numerical simulation tools and codes.

TRANSITION OF MATERIALS AND TOOLS INTO PRODUCTS

The rigorous, gated approaches taken to developing and certifying new technologies require that new technologies and materials be relatively mature by the time system architecture decisions are made. Extensive testing may be required to demonstrate this maturity. Because the time required for developing and certifying new materials is often longer than that for designing and developing product applications, strategies are needed to accelerate the application of new materials that have not yet been qualified.

The committee notes that the advanced technology demonstration (ATD) process has been very successful in introducing breakthrough technologies into DoD platforms and could be used to accelerate the introduction of lightweighting technologies into demonstration systems. A well-managed ATD can reduce the need for testing and compress overall development times, while including all requirements in the design. Thus, ATDs could help to rapidly bridge what has come to be called the “valley of death” between the development of a technology and its implementation in products and processes.

Finding 3: Advanced technology demonstration programs have, in numerous instances, proven to be successful in introducing breakthrough technologies into DoD platforms.

The risk with the ATD approach is the potential for unexpected consequences when using new materials, manufacturing techniques, and designs that have not been rigorously tested. This risk can be mitigated by requiring that all system-level and operational requirements be included in the design and application of new technologies, even if those ATDs address components rather than full-scale systems. Not shortcutting this portion of the approach can significantly reduce the risk to field operations that has been experienced with some ATDs.

By making it possible to design, produce, and evaluate entire vehicles and major components under real-world conditions, ATDs facilitate the use of the rigorous systems engineering needed to exploit the full potential of lightweighting.

Recommendation 3: The DoD should expand the use of ATDs to implement lightweighting technologies rapidly in air, maritime, and land demonstration platforms. To improve the transition value of ATDs for lightweighting, it

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[4] During the course of this study, the Obama Administration announced the new Materials Genome Initiative, which addresses many of these needs. See Chapter 6, Box 6-1.

[5] NRC. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12199.

[6] During the course of this study, the Obama Administration announced the new Materials Genome Initiative, which addresses many of these needs. See Chapter 6, Box 6-1.

is important that the DoD incorporate all system and operational requirements into projects, so that lightweighting technologies can be fully optimized from the outset.

Chapter 6 contains a list of possible committee-proposed guiding principles for developing effective lightweighting ATD projects.

MANUFACTURING CAPABILITIES AND AFFORDABLE MANUFACTURING TECHNOLOGY TO FACILITATE LIGHTWEIGHTING

Lightweighting of vehicles poses particular manufacturing challenges. Improvements are needed in joining technology; parts consolidation and miniaturization; tool-less fabrication of low-volume production parts; nondestructive examination methods; and virtual process modeling. Consideration must also be given to the production of structural commodities in particular forms (such as plates and resins), the capability for which may reside outside the United States. Enhancement of fabrication technology is also needed for advanced fibers and composite materials, which in some cases are also available primarily from overseas sources.

The declining domestic capability for manufacturing hampers the ability of the DoD and commercial organizations to achieve the integrated lightweighting solutions inherent in the committee's definition of lightweighting. At the same time, support for the manufacturing capability needed for lightweighting could be part of a national strategy to rebuild cutting-edge manufacturing capabilities in the United States.

The committee believes that the DoD's Manufacturing Technology (ManTech) program has an appropriate framework for the development of advanced lightweighting strategies. However, the current focus of ManTech projects is to address a tightly defined manufacturing challenge and show a direct transition to a specific military platform.

Domestic manufacturing capabilities for advanced materials and for military applications using them are limited or even declining in some areas, particularly when there is no parallel commercial demand for lightweight transportation systems. The boom-to-bust cycle that ties defense contractors to the DoD's procurement cycle threatens the maintenance of a robust defense industrial base.

Aerospace defense contractors have benefited from using similar or the same materials and lightweighting technologies in defense and commercial markets, both of which are driven by the effect of weight on system capability and cost. For land combat vehicles, there is a parallel commercial market in heavy wheeled equipment and heavy trucks that may afford opportunities. The U.S. maritime industry also has the opportunity to benefit from military and commercial overlap, as indicated by the U.S. Navy's joint high-speed vessel and littoral combat ship, which are derivatives of fast-ferry designs developed overseas.

The economic viability of fast ferries is extremely weight-sensitive. If a viable, national high-speed ferry network were to develop, it would have the potential to foster a domestic, competitive capability for manufacturing lightweight ships.

Finding 4: The cost of fielding military systems that incorporate lightweighting solutions is high in part because production volumes are low and performance requirements are highly exacting. The focus on reducing acquisition costs has resulted in increased reliance on foreign technology sources,[7] thus eroding U.S. strategic manufacturing advantages. The problems are exacerbated by the lack of parallel commercial markets that could significantly reduce the costs of technology development and make initial investments more attractive.

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[7] "DOD Undertakes Crash Study on Defense Industrial Base," *Manufacturing & Technology News,* May 31, 2011, Vol. 18, No. 9, pp. 1-2; "DOD Industrial Policy Shop Adds Manufacturing to Its Mission," *Manufacturing & Technology News,* April 29, 2011, Vol. 18, No. 7, p. 7; "Rising Labor Costs in China Are Still 96% Lower Than Those in the US," *Manufacturing & Technology News,* April 15, 2011, Vol. 18, No. 6, pp. 3-4.

Recommendation 4a:[8] The DoD should establish broad manufacturing initiatives—using the ManTech program framework as a model—that encompass a variety of lightweighting strategies, materials, and technologies, with the goal of achieving quantum improvements in performance, affordability, sustainability, and reliability.

Recommendation 4b:[9] In concert with other government agencies, the DoD should explore the merits and requirements of parallel commercial markets that could reduce the development and acquisition costs of military vehicles as well as accelerate the availability and use of lightweighting materials and technologies.

CRITICAL MATERIALS

Finding 5: The committee believes that there remains insufficient high-level DoD awareness of and stratetic vision for ensuring sustained domestic supplies of materials that are essential to the realization of effective lightweighting and would facilitate revolutionary advances in military systems. Although there is growing recognition of the importance of individual metals and rare-earth elements, the domestic availability, supply, sustainment, maintenance, and manufacturing of lightweighting-enabling materials, such as high-performance SiC fibers, thick-section magnesium, and polyethylene fibers, must become targeted priorities of the DoD for lightweighting to become widespread.

One existing program, the Defense Production Act Title III program, includes a number of materials projects relevant to lightweighting, such as production of SiC powder for ceramic armor, low-cost titanium, and continuous-filament boron fiber, but does not include some of the materials and manufacturing processes that the committee believes would have the greatest impact on lightweighting.

The cost of advanced materials extraction, reduction, and processing can be prohibitive, and there is a lack of domestic manufacturing infrastructure to fabricate the primary metal alloys or the intermediate engineering forms, or to manufacture final, shaped products. This lack of infrastructure affects opportunities for use of lightweighting materials in defense and civilian applications.

Recommendation 5: In cooperation with other agencies, the DoD should establish a federal investment strategy that (a) determines which structural materials are most important to future lightweighting and (b) establishes the resources to ensure continuous development of these materials and their associated manufacturing processes.

As part of this holistic approach, the existing Title III program should be expanded to include a larger number of materials critical to lightweighting of military aircraft, vessels, and vehicles. In expanding the program, the DoD should recognize the need for the long-term, continuous development of these materials and of the manufacturing techniques and capacity needed to produce them.

SUMMARY COMMENTS

In summary, the committee's view is that lightweighting materials, design, and technologies could have far-reaching benefits: implementation of lightweighting as defined above not only would address optimization of military vehicles but also could have security and economic benefits for the nation:

- *Energy use.* Reduced energy consumption and cost for both military and commercial vehicles;
- *Competitiveness.* Increased competitiveness of future U.S. products stemming from system-level integration of materials science and engineering; and
- *Jobs.* Preservation and creation of high-end jobs in manufacturing and engineering.

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[8] During the course of this study, the Obama Administration announced the new Advanced Manufacturing Partnership, which could address many of these points. See Box 6-2.

[9] During the course of this study, the Obama Administration announced the new Advanced Manufacturing Partnership, which could address many of these points. See Box 6-2.

1

Background and Motivation

1.1 LIGHTWEIGHTING: BACKGROUND

Reducing the weight of military vehicles has been of interest to the U.S. Department of Defense (DoD) for decades. Over the years, many reports and projects have considered lightweight and otherwise advanced materials for use in DoD systems. Historically, reducing the weight—or "lightweighting"—of military land vehicles, maritime vessels, and aircraft has been motivated by the desire to reduce fuel use and costs and the need to improve vehicle transportability.

Reducing DoD fuel consumption and costs remains a critically important reason for lightweighting. The fully burdened cost of fuel for U.S. military operations—including acquisition and transportation costs—approaches $1 billion/day.[1] Reducing fuel consumption could also help reduce the risks to personnel and operations associated with supplying fuel to deployed forces.

Today, however, there are further motivations for lightweighting military vehicles, as illustrated by the "iron triangle" of requirements shown in Figure 1-1. The military is constantly seeking to balance the three sides of the triangle: performance, protection, and payload. (Not shown is affordability, which is also a crucial consideration.) The current combat situation has made achieving an appropriate balance increasingly demanding, with weight a contributing factor: for instance, the "uparmoring" that has occurred in military ground vehicles deployed overseas over the past decade has resulted in very large weight increases that have, in turn, had adverse effects on vehicle maneuverability and range.[2] To the extent that lightweighting can restore some or all of the lost performance, it can help to rebalance the "iron triangle."

Lightweighting can improve a vehicle's performance and reduce its support needs. For instance, it can improve maneuverability, transportability, speed, and range—all important attributes for military vehicles. It can also be used to "buy" more payload capacity (weight) in the form of personnel or materiel. For aircraft, lower weight is a critical determinant of performance, payload capacity, maneuverability, and range. For maritime vessels, lightweighting of superstructures improves stability, maneuverability, and speed. These possible improvements illustrate

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[1] Fuel for U.S. military operations is managed and provided through the Defense Logistics Agency's Energy Support Center (DESC) group. See http://www.desc.dla.mil/. Last accessed October 19, 2011.

[2] M. Grujicic, H. Marvi, G. Arakere, W.C. Bell, and I. Haque. 2009. "The Effect of Up-armoring of the High-mobility Multi-purpose Wheeled Vehicle (HMMWV) on the Off-road Vehicle Performance." *Emerald Insight*, Volume 6, Issue 2, pp. 229-256.

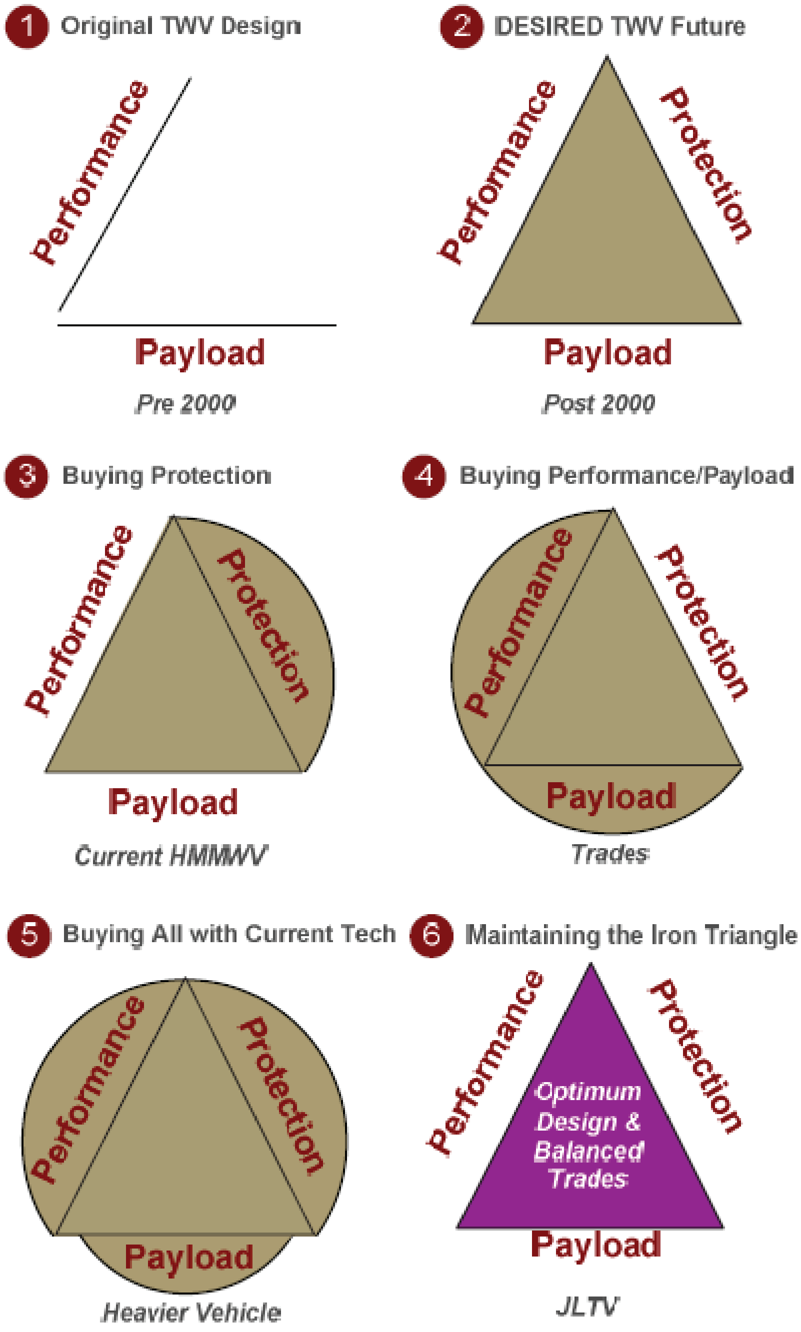

FIGURE 1-1 The “iron triangle.” SOURCE: Adapted from G. Bochene, TARDEC, presentation to the 2007 Combat Vehicles Conference, October 24, 2007.

that viewing lightweighting through the lenses of fuel efficiency and transportability alone is too restrictive and fails to capture the full potential for lightweighting to help balance the "iron triangle."

This potential can be realized through various means. Lightweighting has traditionally been viewed narrowly, as a process of replacing the materials in a system with lighter[3] alternatives. Although this is indeed one way of reducing weight, lightweighting can be achieved in many other ways: for instance, by changing structural shape (I-beams, tubular members, and lattices being common examples) or tailoring the spatial configuration of dissimilar materials (as is done with fiber composites and sandwich panels) to make the most efficient use of each material. These strategies are now routinely taught in undergraduate engineering programs, especially in the materials and mechanical engineering fields. Prescriptions for this type of design—using material performance indices, shape factors, and the like—are described in the textbook *Materials Selection in Mechanical Design* by Michael Ashby.[4]

Moreover, sophisticated software tools—such as the Granta CES Selector—are available that aid designers not only in selecting the materials and materials processing methods to use, but also in optimizing performance, cost, and environmental properties. They are becoming ubiquitous in academia and the industrial design community.

Lightweighting can be achieved at a systems level, which involves considering the potential for lightweighting from the beginning of the design process. For example, creative architectural designs that involve multifunctionality in components or make use of multifunctional materials can emerge when lightweighting approaches are integrated into the engineering of new systems. A systems-level perspective also incorporates considerations such as the availability of materials and of the manufacturing processes used to produce them and to create shaped parts. The broad view of lightweighting that the committee has adopted is likely to yield the greatest benefits for balancing the "iron triangle."

1.2 STUDY CHARGE AND SCOPE

Recognizing the substantial remaining potential for lightweighting in air, sea, and land vehicles, especially when approaches beyond just lightweight materials are considered, the Department of Defense (DoD), through the Reliance 21 Community of Interest on Materials and Processing,[5] asked the National Research Council (NRC) to assess the current state of lightweighting in land vehicles, aircraft, and maritime vessels and recommend ways in which lightweighting might be better implemented in the future. The statement of task, given in Box 1-1, called for a study that would focus on military vehicles, but also address commercial vehicles.

The Committee on Benchmarking the Technology and Application of Lightweighting was asked explicitly to look beyond materials alone[6] and to also consider lightweight design, the availability of lightweight materials from domestic manufacturers, and the performance of lightweight materials and their manufacturing technologies (the technologies used to process and manufacture the materials as well as those used to manufacture components, structures, and other shapes from the materials). It was asked to consider the full "trade space" of attributes—that is, the effect that lightweighting strategies can have on all aspects of vehicle function and performance. The need

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[3] "Light" and "lightweight" are terms used in this report to denote materials having high specific properties (e.g., high specific strength, defined as strength divided by density) or, more generally, high specific performance. Historically, lightweighting has been achieved by focus on lower-density materials with high property values (e.g., composites). However, the converse is equally viable—using traditional-density materials with enhanced property values, which then allow reduced total weight via reduced cross sections.

[4] Michael Ashby. 2011. *Materials Selection in Mechanical Design.* Edition 4. Burlington, Mass.: Butterworth-Heinemann.

[5] Reliance 21 is a management process developed by the Director of Defense Research and Engineering (DDR&E), with the advice of the Defense Science and Technology Advisory Group, involving the science and technology executives of all the military components. It was launched in 2008 as a means of improving coordination and collaboration among the components and reducing unnecessary duplication (Statement of Honorable John J. Young, Jr., Director of Defense Research and Engineering, before the U.S. House of Representatives Committee on Armed Services, Subcommittee on Terrorism, Unconventional Threats, and Capabilities, March 21, 2007, available at http://www.globalsecurity.org/military/library/congress/2007_hr/070321-young.pdf). All the DoD and military service science and technology (S&T) organizations prepare biennial S&T strategic plans that are informed by and harmonized with an overarching DoD S&T strategic plan prepared by the DDR&E (see www.dod.gov/dodgc/olc/docs/TestYoung070321.doc).

[6] "Background Information and Study Goals," presentation to the committee by Julie Christodoulou, Director, Naval Materials Division, Office of Naval Research, July 20, 2010.

Box 1-1
Statement of Task

The committee will assess the current state of lightweighting implementation. To do so, the committee will:

Task I	Assess the relevance of the definition of lightweighting within the materials community.
Task II	Assess and benchmark the current state of lightweighting implementation in land, sea, and air vehicles in the military and civil sectors, with a primary emphasis on military systems and equipment.
Task III	Make recommendations for ways in which the use of lightweight materials and lightweight solutions might be better implemented in military and dual-use systems.

As part of its assessment, the committee will consider:

- The use of lightweight materials and lightweight design.
- The availability of lightweight materials from domestic manufacturers.
- The performance of various lightweight materials and manufacturing technologies.
- The trade space (that is, the impact that use of lightweight materials will have on the required performance and function of various systems, platforms, and components) for determining the value of lightweighting.

for a systems-level approach, wherein lightweighting is considered from the beginning of the design process, provided important context for the committee's work.

1.3 COMMITTEE'S APPROACH AND REPORT OUTLINE

To stay within the constraints of available time and resources, the committee chose to focus its efforts as indicated below:

1. The committee considered its primary topic to be military vehicles. Although it drew on experience with lightweighting in civilian vehicles, it did not address these vehicles in detail.
2. The committee did not have the resources to perform a comprehensive assessment of the state of lightweighting across the services, or to "benchmark" lightweighting implementation.[7] It instead reviewed illustrative examples of lightweighting in military and civilian systems as a way of identifying qualitative lessons for future efforts. It also outlined some barriers that impede lightweighting as well as opportunities for further lightweighting.
3. The committee considered the "trade space" of vehicle attributes qualitatively. A quantitative assessment of the value of lightweighting would require development of a set of performance metrics that describe quantitatively the changes in each attribute for a unit change in weight. Examples of metrics include fuel use and expenditures over the life of the vehicle; the frequency and cost of repairs; the number of occupants or amount of payload and armaments that can be carried; the transportability of a vehicle (e.g., whether it can be carried on a certain platform); the maximum speed and range; and resistance to blast and other threats. In this context, it is clear that no single performance metric can fully describe "the value of a pound saved."

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[7] By definition, benchmarking requires quantitative measurement of performance. Acquiring the data needed for such measurements was not feasible, not only because of the limited time and resources available to the committee, but also, and more importantly, because of the proprietary nature of the requisite information.

4. The committee considered the development of vehicle and body armor to be outside the study scope. It focused on the structural elements of vehicles and their components. Lightweighting can facilitate the use of heavier armor, but the report does not discuss this in detail. (Nor does it discuss other non-structural elements such as energy storage systems, electronics, cables, cartridge cases, and so on.) Optimizing vehicle attributes within the "iron triangle" will require consideration of the full system, including all vehicle internals as well as vehicle armor and perhaps even the weight of body armor worn by vehicle occupants.

   For a recent assessment of opportunities for developing advanced materials for use in vehicle and body armor systems, see the NRC report *Opportunities in Protection Materials Science and Technology for Future Army Applications.*[8]
5. The committee drew heavily on earlier studies. Numerous reports over the past decade have advised the DoD on topics related to lightweight or otherwise advanced materials. Other reports have addressed related topics, such as technology transition and systems engineering, that are central to the broad view of and approach to lightweighting that the committee has adopted. Later in this chapter, the committee summarizes the key findings and recommendations of some of those studies.

In summary, the committee's approach was to provide an overview of lightweighting considerations for military vehicles, and to supplement that overview with detailed examples from the military and commercial sectors, with some assessment of "lessons learned." This report brings together a range of pertinent information that the committee hopes will be useful in efforts to foster better implementation of materials and design for lightweighting of military vehicles.

To assess the relevance of the definition of lightweighting within the materials community, the committee considered the multiple objectives that military air, sea, and land vehicles are obligated to meet and the varied benefits that lightweighting can confer. Based on these factors and its own collective experience, the committee developed a working definition of lightweighting, presented in the next section, that reflects a broad view of lightweighting and provides the framework for this study. The subsequent section contains a qualitative assessment of the relative importance of lightweighting for different types of vehicles. The remainder of Chapter 1 introduces some key topics in lightweighting and reviews the findings of earlier studies, as described under item 5 above.

To assess and benchmark the current state of lightweighting implementation in land, sea, and air vehicles, with a primary emphasis on military systems and equipment, the committee reviewed examples of lightweighting, the barriers that impede use of this approach, and some opportunities for further lightweighting. The assessments for air, sea, and land vehicles appear in Chapters 2-4.

After considering air, sea, and land vehicles separately, the committee returned to some of the points introduced in Chapter 1. Chapter 5 expands on some topics that cut across all vehicles, in some cases identifying areas where further work is needed. That review, together with the assessment in Chapters 2-4, laid the groundwork for the committee's formulation of recommendations for ways in which lightweighting might be better implemented. These recommendations are presented in Chapter 6.

1.3.1 Approaches for Chapters 2 Through 4 on Air, Sea, and Land Vehicles

As noted earlier, weight is a critical determinant of aircraft performance, payload capability, maneuverability, and range. Optimizing the weight of aircraft relative to other performance elements (and costs) has been a focus of the aircraft industry, both commercial and defense, for decades. Therefore, the chapter on aircraft comes first, followed by the chapters on maritime vessels, and land vehicles. Chapter 2 provides detailed discussions of some topics, such as the use of composites; these discussions are referred to in Chapters 3 and 4.

Each of the three chapters addresses Task II for the type of vehicle (air-, sea-, or land-based) discussed as well as the bulleted items (see Box 1-1) that the committee was asked to consider. The first four sections of each

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[8] NRC. 2011. *Opportunities in Protection Materials Science and Technology for Future Army Applications.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=13157. Last accessed on November 17, 2011.

chapter review (1) how and why lightweighting is used and the status of metrics; (2) barriers and keys to success in lightweighting, including some brief examples; (3) opportunities for lightweighting via new materials, designs, and manufacturing processes, focusing on the near term; and (4) long-term challenges to lightweighting. Each chapter ends with examples of vehicle development and the role of lightweighting therein. As noted above in describing the committee's approach to this study, these examples take the place of a full benchmarking effort. They are reviewed as illustrations of how lightweighting has been attempted and sometimes achieved and what lessons might be learned from the experiences.

Chapter 3 covers heavy ships as well as lighter maritime craft, for all services. Chapter 4 focuses on heavy military combat vehicles, although it does provide an example of systems engineering as applied to a commercial product, the Ford F-150 truck. Chapter 2 on aircraft has much more coverage of commercial applications and concentrates primarily on composites (although other materials are discussed).

Finally, lightweighting also applies to unmanned vehicles. For robotic vehicles (air, sea, and land) as for manned vehicles, lightweighting serves to improve performance as well as transportability, which in this case can extend to "man-portability."

The committee did not do a full review of unmanned vehicles. It does provide examples of unmanned air vehicles but did not review unmanned maritime vehicles (surface and underwater) or unmanned ground vehicles. In the committee's view, for land and maritime applications, balancing the sometimes-competing requirements (performance, survivability, operational supportability, and so on) is currently most important for occupied vehicles. Hence, these are the focus of Chapters 3 and 4. Unmanned air vehicles (UAVs), which have been in use for some time, are discussed in Chapter 2.

1.4 DEFINING LIGHTWEIGHTING

The notion of lightweighting is seemingly simple. At its core, lightweighting is the process of reducing weight for the purpose of improving performance. However, as noted above, it goes far beyond simply using low-density and otherwise lighter and high-performance materials to improve fuel efficiency. Indeed, it encompasses a wide range of implementation strategies—the use of low-density materials being only one possibility. For example, lightweighting can be accomplished by efficient utilization of materials through judicious materials selection and design optimization—that is, finding the best material in the best geometric configuration for each part of the system. It can be accomplished by developing components that serve multiple functions, thus simplifying design, or by improving manufacturing methods so as to enable the use of new materials. In the committee's view, establishing and maintaining a broad vision of what constitutes lightweighting are necessary to achieving the greatest benefits.

The committee views lightweighting as a means of not only reducing fuel consumption and costs and the associated logistical requirements but also achieving a variety of desirable features. The definition of lightweighting established by the committee and used in its assessments is shown in Box 1-2.

Box 1-2
Committee's Definition of Lightweighting for Military Systems

The committee developed the following broad definition of lightweighting:

Lightweighting is the process of reducing the weight of a product, component, or system for the purpose of enhancing certain attributes, notably (1) performance, (2) operational supportability, and (3) survivability.

Note that, although this definition also applies to civilian vehicles, the main focus of the report is military vehicles, and so the attributes of interest and the wording used are tailored for military applications.

Each category of vehicle attributes is broad in scope:

- *Performance* includes vehicle speed, maneuverability, payload capacity (in terms of weight), and range. In this context, lightweighting is assessed on the basis of the degree to which these attributes are enhanced when lightweighting materials and design are used.
- *Operational supportability* refers to the ease and cost associated with support of vehicle operation. It encompasses fuel consumption as well as transportability, durability, reliability, maintainability, and repairability. These attributes are related to performance, but are of critical importance to overall system effectiveness, and so must be concurrently or iteratively optimized with other key system attributes. Long-term sustainment (support of fielded systems and their subsequent life cycle product support, as well as modernization of legacy systems) also falls into this category, although the committee did not assess sustainment needs.
- *Survivability,* in principle, could be considered under *performance*. However, the committee treated it separately because of its crucial importance to military systems and the strong correlation between weight and survivability for some vehicles. Survivability includes attributes such as resistance to blast and ballistic threats, tolerance of damage and environmental conditions, and avoidance of detection.

Lightweighting can confer other benefits not called out specifically in the committee's definition—notably, flexibility and adaptability. One example is the Army's A+B approach, wherein the base vehicle, denoted "A," can be equipped with various armor packages, denoted "B." This approach allows not only for the armor packages to be matched to the current threat levels but also for rapid integration of new armor packages as technologies improve or threats evolve. One negative consequence of this approach is that the vehicle will not be optimal for conditions demanding high speed and maneuverability but requiring only light armor, because the base vehicle must be sufficiently robust (and hence, usually, heavier) to bear heavier armor under other circumstances.[9] To the extent to which the base vehicle can be made lighter, this disadvantage can be reduced.[10]

Legacy systems will undoubtedly be used in the future under conditions that push the envelopes of their original designs. Similarly, future systems will necessarily be designed based on the performance, operational, and survivability requirements set at the time of design. The inevitable evolution in the conditions under which the vehicles will be employed emphasizes the need for *flexibility and adaptability* in their design—e.g., through designing so as to facilitate component replacement or other types of upgrades—to allow the military to respond rapidly to changing threats and priorities and carry out long-term sustainment as efficiently as possible.

It is now widely recognized that taking fullest advantage of lightweighting requires a systems-level approach.[11]

In making its assessments of lightweighting in air, sea, and land vehicles, the committee assigned qualitative rankings of the importance of each general class of attribute to each class of vehicle, with 1 the most important and 3 the least important. These rankings, summarized in Table 1-1, were developed based on the presentations made to the committee at its meetings and the collective experience of committee members. They represent the committee's view at the time this report was prepared.

Under the committee's broad definition, lightweighting demands a true systems approach. Focus on only one vehicle attribute may result in a weight reduction but miss the more significant benefits that could be attained through a more systematic consideration of lightweighting throughout a vehicle systems design cycle. A systems approach to design might consider:

- Materials with high specific strength or performance (low-density materials are a subset of this category);
- Creative architectural and component designs that make the most efficient use of materials;
- Integration of materials selection with novel design concepts to achieve multifunctionality;

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[9] "Ground Systems Integration Domain (GSID) Materials for Ground Platforms," presentation to the committee by Lisa P. Franks, U.S. Army, Tank and Automotive Research, Development and Engineering Center, Research, Development and Engineering Command, September 2010.

[10] This is also true for reducing the weight of armor, but as noted earlier, armor is beyond the scope of this study.

[11] See, for example, Center for Automotive Research, 2011, "Automotive Technology: Greener Products, Changing Skills Lightweight Materials & Forming Report." May. Available at http://drivingworkforechange.org/reports/lightweightMaterials.pdf.

TABLE 1-1 Lightweighting Attributes and Their Relative Importance for Land Vehicles, Maritime Vessels, and Aircraft

		Relative Importance		
General Attributes	Specific Attributes	Land Vehicles	Marine Vessels	Aircraft
Performance	• Speed • Maneuverability • Payload • Range	Primary 2	Primary 2	Primary 1
Operational supportability	• Fuel consumption • Maintainability • Durability • Reliability • Repairability • Sustainment	Secondary 3	Secondary 3	Primary 2
Survivability	• Ballistic impact resistance • Explosion resistance • Damage tolerance • Observability	Primary 1	Primary 1	Secondary 3

NOTE: These rankings represent the committee's view at the time this report was written. 1, 2, and 3 represent the committee's assessment of the relative importance of each attribute for a given transport platform. For example, for land vehicles, survivability is the most important of the three attributes, and operational support capability is least important (although it is still important in absolute terms). "Primary" and "secondary" represent the relative importance of an attribute across air, sea, and land vehicles. For example, operational support capability is a primary consideration for aircraft but of secondary importance for land vehicles and marine vessels. Note also that the "Aircraft" category contains all aircraft flown by the military: fighters, transports, and UAVs. This aggregation lowers the ranking of survivability from what it would be for fighter and attack aircraft alone.

- New or advanced manufacturing methods that enable the use of new designs, materials, and materials combinations as well as the reduction in manufacturing defects (thus improving durability and service life); and
- More aggressive design strategies to optimize structure and function, based on (a) optimization of system design and topology using available or new technologies and components, and (b) improved understanding of response and failure mechanisms of materials and improved associated physics-based computational models.

Although the committee found good examples of vehicle lightweighting in all three areas (air, sea, and land), there is still much that can be done. Viewing lightweighting broadly, and at the systems level, may help bring these opportunities to light.

1.5 KEY TOPICS IN LIGHTWEIGHTING

This section introduces topics that apply to all vehicles and are mentioned in the air, sea, and land chapters. Chapter 5 discusses some of these topics in greater depth.

1.5.1 Systems Engineering, Design, and Optimization

As mentioned above, and discussed in the review of earlier reports that appears later in this chapter, it is widely recognized that taking the fullest advantage of strategies such as lightweighting demands a true systems approach. Importantly, a systems approach to lightweight design need not be materials-centric: it extends to how materials are arranged, topologies optimized, and functionalities combined. Many of the innovations in lightweight construction are concerned with putting material where it is most beneficial, and advances in system design and topology can yield improvement in performance even absent the incorporation of new materials. For example, advances in the performance of America's Cup yachts have stemmed in large part from changing the shape of the boat. Multifunctional structures—such as those that provide both structural support and protection from fire—reduce "parasitic" weight (e.g., for elements that protect against fire but have no other function). Improvements in manufacturing of large components from particular materials can allow those materials to be used for additional applications.

Systems-level design requires simultaneous consideration of all the ramifications of changes in materials or design and the corresponding trade space—that is, how various performance and other attributes change relative to one another in response to a material or design change. It also requires definition of the relative importance (or weighting) of the attributes in order to develop optimal designs.

In its definition of lightweighting (see Box 1-2), the committee separated vehicle attributes into the three categories of performance, operational supportability, and survivability for discussion purposes and to illustrate the challenges involved in optimizing the "iron triangle" of requirements (see Figure 1-1). However, it notes that such optimization will always have to be done concurrently for all important attributes—and that systems engineering may in fact consist of sequential analyses for different attributes, followed by iterations in design and configuration, until all key requirements are satisfied or optimized for the desired system.

A fuller discussion of systems engineering appears in the review of previous studies later in this chapter, and also in Chapter 5. This topic is also mentioned in Chapters 2-4; Chapter 4 contains an example of full systems engineering design: the Ford F-150 truck. Chapter 5 also discusses work in structural design or topology.

1.5.2 Development Cycles for Materials and Vehicle Systems

The time required to develop new materials and their processing technologies, and certify new materials for use in military vehicles, generally exceeds that required to develop and certify a new vehicle. Specifically, a critical limitation to the introduction of new materials into military vehicles is the extended period required for materials development and qualification. The time required can vary widely—from 2 to 3 years for derivative materials on an expedited schedule, up to a decade or longer for significant new or emerging materials or processes. In cases where a new class of material is under development or where new infrastructure is required to produce the material or structure, the time period can extend well beyond 10 years,[12] often as long as 15 years[13] and even up to 20 years when a new, advanced material system is involved.

As discussed in Chapters 2-4, the time to develop a new vehicle can be much shorter, although this is not always the case. The reasons for the lengthy materials development and qualification cycle are described in a 2003 NRC report:

> At the front end of the development cycle is the arduous task of creating a material with superior properties. Not only must the composition of the material be established, but—of equal importance—so must the process by which the material is made. Processing of structural materials is critical because the microstructure developed during processing is a primary determinant of the resultant mechanical properties. Complicating the design process is the fact that a material has many mechanical and physical properties, e.g., elastic modulus, yield strength, ductility, fracture toughness, fatigue resistance, density, weldability, and corrosion resistance. Improvement of one property often causes degradation of another. Hence material design is a compromise. Traditionally, the development cycle is long because it involves sequential synthesis of the material and then extensive testing of many properties and combinations.[14]

The lengthy materials development cycle means that new materials and process technologies must be suitably mature at the time of preliminary design to ensure that the target vehicle will be manufactured within the required timeframe; otherwise, sometimes-costly risk mitigation strategies must be implemented. An adequate,

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[12] NRC. 2004. *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=11108. Last accessed November 17, 2011.

[13] NRC. 2003. *Materials Research to Meet 21st Century Defense Needs.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10631. Last accessed November 17, 2011.

[14] Ibid.

stable supply of materials must be established, together with adequate manufacturing capability to produce useful forms of these materials, in order to ensure that the capability exists for streamlined incorporation (also called "insertion") of lightweight materials into designs.

In addition, the current acquisition process for military vehicles is expensive and lengthy.[15] Examples include the F-22 Raptor (19 years)[16] and the F-35B (9 years, although not a function of technical barriers).[17] The time and expense involved stem from the extensive validation and certification required for new materials and processes as well as the exhaustive testing of full-scale systems that must be done. Because the consequences of failure are severe, the principal decision makers tend to be strongly risk-averse.

The time required to design and certify vehicles and products is generally much shorter. The product design and development cycle outpaces the materials development cycle by a significant margin, leading to a mismatch that hampers the insertion of new materials into engineering products.

The "gated" processes that are followed for development of new products or systems, such as the process specified by the Defense Acquisition Guide and DoD Instruction 5000.02, require technologies to be relatively mature before insertion at the initiation of a program. The considerable time and cost required to reach the requisite maturity level for a new material must occur in the preacquisition phase, before a program is actually initiated. This often exacerbates the extent to which the development and qualification cycles for materials and vehicles are "out of sync" with one another, making it even more difficult to insert new materials early in the design cycle.

A more comprehensive discussion of this issue is contained below in the committee's review of earlier reports. It is also discussed in Chapter 5, where some strategies to ameliorate this mismatch are identified.

1.5.3 Integrated Computational Materials Engineering

Integrated computational materials engineering (ICME), and its development over the past 10 years, is discussed in detail in the next section, under the review of earlier reports. ICME tools are discussed further in Chapter 5. In the context of materials and process develoment, ICME is the analog to systems engineering (Section 1.5.1) in vehicle design. For ICME, the "system" is the set of manufacturing processes, materials systems, and engineering applications.

The primary potential of ICME is more efficient and robust engineering of products, manufacturing processes, and materials.[18] Efficiency can take the form of reduced development time, reduced development costs, or better matching of materials and needs. ICME allows quantitative tradeoffs between material properties and manufacturing capabilities. It can lead to the development of new engineering products using existing materials, refinement of existing materials and manufacturing processes, or development of new materials and manufacturing processes. The use and further development of these tools for military purposes would be expected to benefit the development and improvement of commercial air, maritime, and land vehicles.

1.5.4 Physics-Based Models of Material Behavior

Future military technologies will place increasing demands on materials in extreme service environments—notably, under high levels of stress, strain, strain rate, temperature, and heat flux. Tremendous progress has been made over the past two decades in the development of finite element codes for thermostructural analysis. Significant advances have also been made in the development of continuum-level constitutive laws for inelastic deformation, damage evolution, and rupture. Together, the finite element codes and the constitutive laws have proven effective in analyzing structural response over a wide range of loading conditions. Notwithstanding this progress, there remain

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[15] See, for example, NRC, 2011, *Evaluation of U.S. Air Force Preacquisition Technology Development*, Chapter 2, pp. 33-61. Washington, D.C.: The National Academies Press. Available at http://books.nap.edu/catalog.php?record_id=13030. Last accessed November 17, 2011.

[16] Andrew McLaughlin. 2006. "F-22A Raptor—No Longer a Fair Fight." *Australian Aviation,* April, pp. 55-61. Available at http://www.ausairpower.net/AA-Raptor-0406.pdf. Last accessed June 21, 2011.

[17] Bill Sweetman. 2011. "F-35B Put on Probation; New Bomber to Go." *Aviation Week*, Jan. 7.

[18] NRC. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12199.

large gaps in the understanding of the underlying physical processes that operate in complex multiphase systems, especially at very high strain rates and in the shock domain. New information-rich experiments and corresponding material models are needed. Specific areas that require attention include:

- The linkage of strength, damage evolution, and fracture to material chemistry, processing history, and microstructure;
- Techniques to bridge time and length scales in material models; and
- New numerical techniques to model the pertinent physical processes with high fidelity and exploit the computational power now available to the DoD.

The U.S. Department of Energy has sponsored extensive work in physics-based modeling and simulation at its national laboratories, much of it to provide assessments of material and structural behavior for nuclear weapons in the absence of testing. The fundamental physics codes developed for this purpose are relevant for all materials design efforts. For example, work at Sandia National Laboratories has resulted in open-source tools for molecular modeling that have been used extensively and are continuously updated to add more fundamental physics information and to increase computational speed. Continued progress on such physics-based modeling and simulation is needed.

1.5.5 Material Properties and Testing

Introduction of new technologies into complex systems typically requires significant experimental testing from the level of material samples (often called "coupons") to components to subsystems. While modeling can accelerate this process, ultimately the new technology must be tested in field conditions as part of a complete system. As noted previously, the mechanical properties of materials are affected by process variations and by the defects induced during their processing. As a result, the as-manufactured properties of materials can differ from properties determined in the laboratory.

For structural materials, the usual development of material properties begins with coupon-level tests to gauge basic physical and mechanical properties. If these data look promising, fabricated panels representative of candidate structure are made and tested. These test data substantiate the coupon test data and provide confidence in the accuracy of design analysis methods.

Subsequently, subscale or full-scale candidate parts are made of the new material for component testing. Throughout this process, the manufacturing processes used to make these test articles may not be the actual production processes. The final design data are developed from test specimens made from material processed using actual production methods. These data are validated through testing of full-scale subsystems incorporating the new material manufactured using the actual production processes.

1.5.6 Uncertainty, Risk, and Design Factors

A key issue with the use of new materials is the use of larger design factors (also referred to as safety factors and knockdown factors) that can increase the weight of a component over that needed to satisfy design requirements. Several concerns and uncertainties drive the increase in design factors. These include:

- Uncertainty in properties of materials (especially local variability in properties);
- Concern over the potential for unknown susceptibility to fatigue or environmental effects;
- Variability in manufacturing processes;
- Difficulty in detecting manufacturing defects in heterogeneous materials by inspection; and
- Shortcomings in the non-destructive evaluation (NDE) techniques that could detect manufacturing defects as well as in-service damage.

A particularly fruitful area for research and development is NDE techniques and technologies. For example, NDE of heterogeneous materials such as fiber composite laminates is challenging. Large defects can be induced during the manufacturing of large composite parts, in which differential thermal expansion can result in fiber rumpling and a loss of local tensile stiffness, or low thermal conductivity of the matrix can lead to regions of incomplete matrix cure or regions of exothermic runaway and over-cure. These are all very difficult to detect and characterize with today's NDE tools.

The processing issues and poor control of microstructure in anisotropic metals such as magnesium or titanium present another class of problems for which a new generation of NDE tools is needed. These tools could be developed for better control of the manufacturing process (to reduce variability), which would reduce the need for costly inspections after manufacturing. Associated issues and challenges, and approaches for overcoming barriers, are discussed in Chapter 5.

1.5.7 Materials and Materials Availability

As discussed in Chapter 5, two cornerstones of lightweighting are (1) low- or reduced-density, high-specific-performance[19] alloys, and (2) fiber-reinforced composite materials. High-strength steels are also important, because even modest improvements in steel strength can have a large impact due to the large amounts of steel used in military vehicles. Some alloys, such as those based on aluminum, are readily available. They are used widely in industry in sufficiently large volumes to support the operations of multiple suppliers.

The availability of other materials critical to lightweighting, however, is limited, or the materials are prohibitively costly. Moreover, the specialized manufacturing capabilities needed to create some of these materials, or to form them into useful structural shapes, are, in some cases, in short supply. These concerns are mentioned in Chapters 2-4 and discussed further in Chapter 5.

1.5.8 Mechanisms for Technology Transition

As is discussed above, acceleration of the insertion or transition of new materials and technologies into products and into use is needed. Three DoD mechanisms for doing this are accelerated insertion of materials, advanced technology demonstrations (and advanced concept technology demonstrations), and ManTech. An NRC report, *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems,* addresses many of the issues involved. A DoD initiative, Accelerated Insertion of Materials, is highlighted in that report.

The advanced technology demonstration (ATD) is a process for managing science and technology programs that brings together all the involved communities—scientific research, technology design and development, end users, and others—to accelerate the maturation of technologies. According to the DoD's *Manager's Guide to Technology Transition in an Evolutionary Acquisition Environment:*

> The collaboration and coordination result in early interaction and exchange among the communities, permit experimenting with technology-driven operational issues, weed out unattainable technologies as early as possible, and result in more focused requirements and capability documents . . . . ATDs require planning, review, and approval at the Service or agency level. ATDs have a finite program duration, agreed-upon exit criteria, and typically require transition plans. Accordingly, ATDs require technologies that are mature enough to provide a capability that can be used or demonstrated during the demonstration period.
>
> The ATD team evaluates technical feasibility, affordability, compliance with operational and technical architectures, operation and support issues, and user needs as early as possible. This fully integrated approach and focus on operationally sound capabilities ensures that militarily significant capabilities can be developed, evaluated, and transitioned to the warfighter rapidly.[20]

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[19] Specific performance (e.g., strength) is performance divided by density.

[20] DoD. 2005. *Manager's Guide to Technology Transition in an Evolutionary Acquisition Environment*. Version 2.0. Ft. Belvoir, Va.: Defense Acquisition University Press. Available at http://www.dau.mil/pubscats/PubsCats/Managers_Guide.pdf.

ATDs are reviewed and approved by the services and funded with service science and technology funds. Specific ATD projects are described in Chapters 2 and 3, and the ATD process is discussed more fully in Chapter 5.[21]

A related approach, the advanced concept technology demonstration (ACTD), is designed to expedite the transition of maturing technologies from the developers to the users. ACTD projects emphasize assessing and integrating technology rather than developing it. The goal is to put a prototype into the field and help the end user evaluate it under realistic conditions, and so the program works with fairly mature technologies.[22]

The DoD's Manufacturing Technology Program (ManTech) is aimed at reducing technology acquisition and total ownership costs by developing, maturing, and transitioning key manufacturing technologies. The program "matures and validates emerging manufacturing technologies to support low-risk implementation in industry and DoD facilities . . . and addresses production issues from system development through transition to production and sustainment. The focus is on rapid responses to immediate manufacturing needs." [23]

1.6 CHALLENGES AND OPPORTUNITIES: FINDINGS OF RECENT STUDIES

Numerous reports over the past decade have advised DoD on topics related to lightweight or otherwise advanced materials. Others have addressed related topics relevant to the committee's broad definition of lightweighting. Among them are several NRC reports published over the past 8 years, including the following:

- *Materials Research to Meet 21st Century Defense Needs* (2003),[24]
- *Use of Lightweight Materials in 21st Century Army Trucks* (2003),[25]
- *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems* (2004),[26]
- *Managing Materials for a Twenty-first Century Military* (2008),[27] and
- *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security* (2008).[28]

The key findings and recommendations of these reports are summarized below. Several of the topics covered in these summaries are treated in more detail in Chapter 5 and form part of the foundation for the committee's findings and recommendations. Also described below are the results of some additional relevant reports.

1.6.1 Materials Research to Meet 21st Century Defense Needs

Opportunities for materials research that could lead to revolutionary defense capabilities by about 2020 were described in the 2003 report *Materials Research to Meet 21st Century Defense Needs*.[29] Among the classes of

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[21] Chapter 5 of this report also notes that the DoD has other technology transition mechanisms available.

[22] DoD. 2005. *Manager's Guide,* p. 3-3: "ACTDs should consider manufacturing and sustainment issues as a part of their programs. The long-term success of ACTD initiatives can be improved by considering all of the manufacturing, sustainment, and operational and support issues."

[23] DoD. 2005. *Manager's Guide,* p. 3-7. Further information on DoD's ManTech Program is available at https://www.dodmantech.com/program/index.asp. Last accessed October 19, 2011.

[24] NRC. 2003. *Materials Research to Meet 21st Century Defense Needs.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10631. Last accessed November 17, 2011.

[25] NRC. 2003. *Use of Lightweight Materials in 21st Century Army Trucks.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10662. Last accessed November 17, 2011.

[26] NRC. 2004. *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=11108. Last accessed November 17, 2011.

[27] NRC. 2008. *Managing Materials for a Twenty-first Century Military.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12028. Last accessed November 17, 2011.

[28] NRC. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12199.

[29] NRC. 2003. *Materials Research to Meet 21st Century Defense Needs.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10631. Last accessed November 17, 2011.

Box 1-3
Multifunctional Materials

The following description is excerpted as indicated below.

> One way to reduce weight and volume is by using materials that can perform at least two functions (e.g., stealth and structural support). Multifunctionality can be thought of on two scales: (1) mesoscopic (e.g., coatings) or macroscopic (e.g., load-bearing), and (2) microscopic or nanoscopic, in which multiple physical phenomena are produced through molecular design or architectural texture.
>
> The concept of multifunctionality encompasses many classes of materials and applications: Structural materials may be self-interrogating or self-healing, provide stealth, or protect against enemy fire; microscopic materials or systems may combine sensing, moving, analyzing, communicating, and acting.
>
> The concept of multifunctional materials applies to all the major classifications of materials (polymers, metals, ceramics), but by its very nature it is most prevalent in composites of these materials.
>
> One way to achieve multifunctionality is through functionally graded materials that have properties and material constituents on one surface that differ from those on another surface, or are stratified through the interior of a part.
>
> Any material classified as “smart” or “intelligent” is also multifunctional, usually due to microstructural/molecular level response characteristics that manifest as macroscopic actuation ability with electric, magnetic, or thermal input.
>
> An important global issue related to multifunctionality is therefore the understanding and modeling of materials in a hierarchical fashion to address key length scales.

SOURCE: NRC. 2003. *Materials Research to Meet 21st Century Defense Needs.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10631. Last accessed November 17, 2011.

materials examined, the ones most relevant to the present study were structural and multifunctional materials (see Box 1-3).

The study concluded that the research area of highest priority is materials design by computation (see Box 1-4), which would provide the capability not only to design better materials but also to better understand their behavior, to design better structures with them, and to shorten the development cycle from concept to implementation by eliminating much experimental synthesis and testing.

However, to replace experimentation, computational tools must be reliable: they must consistently predict a suite of mechanical, physical, and thermodynamic properties of materials. The most challenging tasks on the path to robust computational materials design over the next two decades were identified as prediction of equilibrium phase stability in multicomponent materials; prediction of thermomechanical processing transitions (including nonequilibrium phase transformations and microstructure evolution); and prediction of mechanical behavior. Although not couched in the same terms, these elements form the basis for ICME—a concept described in detail in Section 1.6.5 of this chapter.[30]

Another issue identified in the 2003 study is service-induced material changes. If materials and structures are to be designed for performance, it is necessary to understand the evolution of their properties and performance during use. This approach highlights the need for science-based constitutive theories of property evolution as well as the need for virtual engineering and simulation during design. The advantages of such an approach would be reduction of materials and system development cost and acceleration of the development cycle.

The 2003 study’s Panel on Structural and Multifunctional Materials focused on materials in which one

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[30] NRC. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12199.

Box 1-4
Materials Design Assisted by Computation

The following description is excerpted as indicated below.

In the design of materials assisted by computation, the goal is to implement new materials by integrating constitutive models into a framework that employs finite element method (FEM) calculations. The first-level potentials (electron, atom, dislocation, and microstructure) have to be described to yield time, temperature, and size-dependent models of material behavior for all classes of materials, monolithic and composite. This effort will require more precise understanding of physical phenomena and better computer equipment that can extract the important data from a calculation and also analyze these first-level data. A successful effort would predict possible material properties before development costs are incurred and predict material properties and behavior so that the cost of characterization (e.g., temperature dependence of polymer-based materials) could be reduced. This would not only reduce costs but also accelerate material development, especially the introduction of new materials and materials systems into DoD systems.

SOURCE: NRC. 2003. *Materials Research to Meet 21st Century Defense Needs.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10631. Last accessed November 17, 2011.

might expect major (20-25 percent) performance improvements over the next 20 to 25 years, with "performance improvement" referring to improvement over the current state of the art in six areas: strength, toughness, stiffness, density, environmental resistance, and high temperature capability. The 2003 study concluded that the greatest opportunities exist in composite materials (viewed in broad terms as hybrid multimaterial systems, not simply conventional fiber-reinforced composites) rather than monolithic materials. Because of their multiphase nature and fabrication methods, composite materials offer simple routes for embedded sensors, actuators, and other elements that provide multifunctionality.

Finally, the 2003 study identified the need for integration of non-destructive inspection and evaluation into the design of materials and structures to allow for continuous monitoring of the health of all newly designed structures. Health-monitoring sensors integrated into structures would have to be very small and to be incorporated into the internal structure in places that would be difficult to examine with an outside source.

1.6.2 Use of Lightweight Materials in 21st Century Army Trucks

A study focused specifically on lightweight materials for future military trucks, *Use of Lightweight Materials in 21st Century Army Trucks*,[31] was motivated by the Army's requirements for improved vehicle transportability and mobility. The requirements mandated that Army trucks consume less fuel, undergo significant weight reduction, have reduced logistical footprints, and require less maintenance. The principal findings and recommendations fell into three categories.

First, the study identified promising materials and processing routes that could be developed and deployed over various time periods. The opportunities in the short and medium term included high-strength and stainless steels for truck frames; magnesium extrusions, superplastically formed aluminum, ultrahigh carbon steels, advanced aluminum alloys, and polymer-matrix composites for secondary structural elements; and aluminum and magnesium alloys as well as metal- and polymer-matrix composites for drive-train components. The key material class featured for longer-term development was titanium (for armor plate and springs).

Second, the study highlighted the need to develop databases of the properties of these materials and to develop

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[31] NRC. 2003. *Use of Lightweight Materials in 21st Century Army Trucks.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10662. Last accessed on November 17, 2011.

models for their processing and for predicting the performance of the resulting components. Again, some of the elements of ICME were emerging and being recommended for future research.

Third, the study suggested that the DoD procurement process be modified so that the important performance attributes of trucks would be explicitly defined for original equipment manufacturers. For example, if reduction of the logistical footprint is important, this attribute and a method for measuring it must be defined; if the total cost of ownership is important, this attribute, too, should be defined. Weighting factors for each of the performance metrics also need to be defined. The study recommended further that the Army develop and adopt a consistent life-cycle costing methodology for evaluating alternative technologies and that life-cycle cost be heavily weighted in selection decisions.

1.6.3 Accelerating Technology Transition

Published in 2004, the NRC report *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems* addressed best industry practices for the accelerated transition of new materials and processes into application.[32] Case studies included Formula 1 racing cars and America's Cup racing boats. In these cases, the risk/reward balance favored early adoption of emerging materials technology, encompassing new materials, manufacturing processes, and modeling. The report also reviewed some successes in the military's adoption of technology that were achieved when strong champions shepherded the acquisition process.

The report identified as attributes of successful integrated development teams (1) a "viral"[33] development process featuring rapid iteration aided by modeling and broad communication, (2) design to high-level functional (performance) requirements rather than detailed specifications, and (3) effective and flexible team building. The report surveyed the methods, tools, and databases that have supported accelerated technology transition and identified the achievements demonstrated by the aerospace industry in the Accelerated Insertion of Materials (AIM) initiative as the best example of industry practice (see Box 1-5 and additional discussion in Chapter 5).

Echoing two previous NRC studies of materials and manufacturing, *Accelerating Technology Transition* identified computational materials engineering as the greatest opportunity for accelerating transition. The study recommended a national initiative in computational materials engineering featuring (1) wider dissemination of information on current capabilities, (2) deliberate transformation of computational materials science tools to engineering tools, (3) broader development of fundamental databases, and (4) infusion of a stronger design culture in academic institutions. This recommendation was one more step in the direction of the 2008 ICME study and recommendations, described in Section 1.6.5.

1.6.4 Managing Materials for a Twenty-first Century Military

"Since 1939, the U.S. government, using the National Defense Stockpile (NDS), has been stockpiling strategic materials for national defense."[34] In light of dramatic changes in the U.S. economic and national security environments, the NRC was charged with conducting a study to assess the effectiveness of current policies and legislation regarding management of such materials. Published in 2008, *Managing Materials for a Twenty-first Century Military*[35] assessed the continuing need for and value of stockpiling and identified alternative strategies to ensure the availability of strategic materials to the DoD and its suppliers. The major risks to ensuring the supply of these materials include the increasing global demands for materials, a diminishing domestic supply and processing capability, and the ever-increasing risks of disruptions in global supply chains.

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[32] NRC. 2004. *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=11108. Last accessed November 17, 2011.

[33] In the report, development is termed "viral" to denote that the process "is infectious, providing a seemingly effortless transfer of information and products to others in the team; exploits common motivations and behaviors that are reinforced by the team members' behaviors; takes advantage of other team members' resources and knowledge to find solutions; and scales easily from small- to large-scale implementation."

[34] NRC. 2008. *Managing Materials for a Twenty-first Century Military.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12028. Last Accessed November 17, 2011.

[35] Ibid.

Box 1-5
Accelerated Insertion of Materials Program

The following description is excerpted as indicated below.

> The AIM [Accelerated Insertion of Materials] program is a strategic initiative spearheaded by the U.S. Defense Advanced Research Projects Agency (DARPA) and the U.S. Office of Naval Research (ONR). The AIM program initiative created a new materials development methodology that accelerates the insertion of new materials in order to achieve parity with the engine/platform development/design cycles. The AIM program demonstrated application of integrated science-based mechanistic models in (a) accelerated process optimization at the component level, (b) efficient process scale-up with associated reduced risk, (c) accurate forecast of manufacturing variation with fusion of minimal datasets to enable early adoption, and (d) linking of validated models for process/property tradeoffs in system-level design.

SOURCE: Accelerated Insertion of Materials, QuesTek Innovations website, available at http://www.questek.com/accelerated-insertion-of-materials.html.

The principal finding of the study was that the operation of the NDS in its present form is disconnected both from current national defense needs and from national defense strategies and priorities. Its ineffectiveness was attributed to a number of deficiencies in its structure and operation, including inadequate information about the specific material needs of the DoD and the availability of strategic materials in either domestic or offshore markets. The NDS process was described as being “episodic rather than dynamic” and one that is no longer responsive to changes in world markets in real time.

The study concluded with a recommendation that the Secretary of Defense establish a new system for managing the supply of strategic materials. In taking a lesson from the private sector, the system would embrace the concepts of supply-chain management and only sparingly resort to stockpiling. The supply-chain management would require better assessment of risks of disruption, an ability to anticipate vulnerabilities in the supply chain, and strategies to ensure that the supply chains remain resilient to disruption. This strategy would require more effective information-gathering tools to identify which materials are critical to defense needs (by, for example, annual reporting from the services and the defense agencies), assessment of the availability of these materials both domestically and abroad, the potential for market and geopolitical disruptions, and the demands placed on targeted materials in the non-defense industrial sectors of the United States and other commodity-consuming nations.

A noteworthy development since the publication of that report has been recent work under the Defense Production Act (DPA) Title III. The mission of the program is to “create assured, affordable, and commercially viable production capabilities and capacities for items essential for national defense.”[36] The Title III Program is a DoD-wide initiative under the Director of Defense Research and Engineering (DDR&E). The Air Force serves as executive agent. A category of projects under Title III involves critical technology areas in which U.S. industry leads with respect to research and development but runs the risk of being outpaced by foreign industry in developing production capabilities. In both cases, Title III support encourages and enables domestic firms to improve capabilities to produce higher-quality, lower-cost materials.

1.6.5 Integrated Computational Materials Engineering

Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security, published in 2008, defined integrated computational materials engineering as “the

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[36] Further information on the DPA Title III program is available at http://www.wpafb.af.mil/library/factsheets/factsheet.asp?id=10904 and at http://dod-executiveagent.osd.mil/agentListView.aspx?ID=20. Last accessed October 19, 2011.

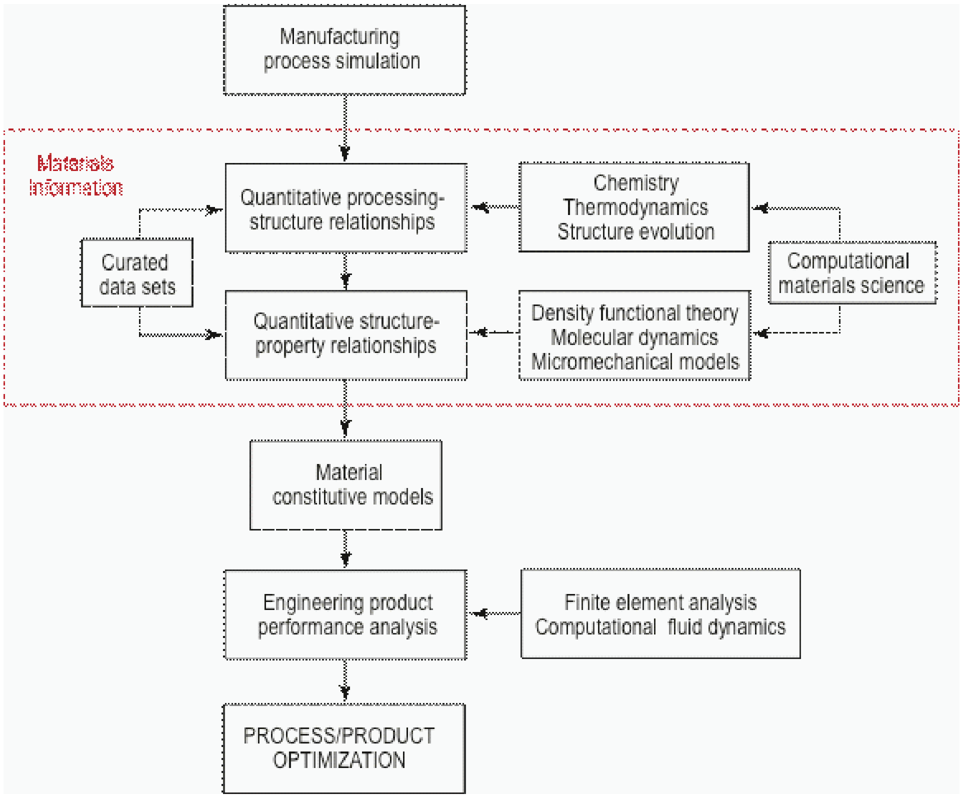

FIGURE 1-2 Integrated computational materials engineering (ICME) flow chart showing how knowledge from different domains is combined to provide manufacturing history-sensitive properties as input for engineering product performance analysis. SOURCE: Adapted from John Allison, 2011, "Integrated Computational Materials Engineering: A Perspective on Progress and Future Steps." *Journal of the Minerals, Metals and Materials Society*, Vol. 63, No. 4, pp. 15-18, DOI: 10.1007/s11837-011-0053-y. April. Available at http://www.springerlink.com/content/t77k837710154345/.

integration of materials information, captured in computational tools, with engineering product performance analysis and manufacturing-process simulation."[37] ICME enables the integration of manufacturing and design via advanced materials models. Its key elements are depicted in Figure 1-2. The report highlighted a number of realized and potential benefits stemming from the use of ICME, the most significant being reductions in development time and cost for new manufacturing processes, new engineering products, and new or improved materials.

Although the report states that the benefits of ICME are clear, the discipline is in its infancy and there are a number of barriers, both technical and cultural, to widespread development and application. The report recommended that future activities in this area focus on the integration of tools and their use for engineering of materials and structures, rather than on computational materials science per se. The report also indicated that high-quality, information-rich experiments are critical to the successful calibration, verification, and validation of ICME tools. While physics-based material models are important in the longer term, partial solutions and empirical models have proven to be effective for development of useful ICME tools. Nevertheless, the need for new physics-based models should not be overlooked. Indeed, efforts on model development should be pursued in parallel with emerging ICME activities and key advancements in models fed into the ICME pipeline when appropriate. The report also

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[37] J. Allison, D. Backman, and L. Christodoulou. 2006. "Integrated Computational Materials Engineering: A New Paradigm for the Global Materials Profession." *JOM*. November, pp. 25-27.

concluded that curated knowledge bases[38] are essential for archiving and disseminating the information required for development of a widespread ICME capability.

In benchmarking best practices, the committee found that development of ICME requires cross-functional teams focused on a common goal—what the report termed a "foundational engineering problem." Foundational engineering problems are those for which a particular combination of manufacturing process, materials system and engineering application can be specified (even in rather broad terms) and for which all aspects of the problem are amenable to computational modeling and analysis. As defined in the report, foundational engineering problems are essentially demonstration projects. They are "foundational" in the sense that they begin to lay the foundation for future larger-scale development and more widespread implementation of ICME tools as well as the infrastructure for educating a future workforce that can effectively exploit these tools.

The report noted that the DoD has played a leadership role as an early champion of ICME and recommended that that role be expanded, in particular by establishing a long-range, coordinated DoD multi-agency program. The specific recommendations to DoD were to (1) identify and pursue foundational engineering problems to accelerate the development and application of ICME to critical defense platforms, and (2) develop an ICME infrastructure of pre-competitive material process–structure–property tools and databases for defense-critical systems.[39]

Recent Activity on ICME

A number of concrete outcomes have taken place since the release of the 2008 ICME report. The first World Congress on ICME[40] was organized and held July 10-14, 2011, in Seven Springs, Pennsylvania; Northwestern University[41] began offering both a certificate program and a new MS program in ICME starting in 2010-2011; and the Materials and Manufacturing directorate of the U.S. Air Force Office of Scientific Research (AFOSR) recently developed a plan to use ICME as an essential organizing concept, adopting ICME throughout its research and development program.[42] The moves by the DoD and the research and engineering community to embrace ICME and take concrete actions in response to the recommendations is of particular importance for implementation of lightweighting in DoD vehicles.

In addition, two recent NRC reports—*Research Opportunities in Corrosion Science and Engineering* (2011)[43] and *Opportunities in Protection Materials Science and Technology for Future Army Applications* (2011)[44]—feature ICME prominently.

- The *Corrosion Science* report postulates grand challenges that involve applying ICME tools and approaches specifically to the problem of corrosion. It notes that computational materials design tools are emerging in physical and mechanical metallurgy but are lagging with respect to corrosion behavior.
- The *Protection Materials* study sought to uncover opportunities for development of advanced materials that are custom-designed for use in armor systems, which are in turn designed to make optimal use of the new materials. Addressing both personnel protection and vehicle armor, the report recommended that the

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[38] "Curated" knowledge bases are managed, centrally available, and standardized collections of data and information, in which the pedigree of all content is documented.

[39] NRC. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12199.

[40] For more information on the first World Congress on ICME, see http://www.tms.org/meetings/specialty/icme2011/home.aspx; last accessed October 19, 2011.

[41] For more information on Northwestern University's ICME graduate programs, see http://www.matsci.northwestern.edu/gradinfo.html. Last accessed October 19, 2011.

[42] See, for example, Katherine Stevens and Chuck Ward, "Air Force Adoption of ICME for Materials and Manufacturing R&D," presentation at the annual TMS meeting, 2011.

[43] NRC. 2011. *Research Opportunities in Corrosion Science and Engineering.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=13032. Last accessed on November 17, 2011.

[44] NRC. 2011. *Opportunities in Protection Materials Science and Technology for Future Army Applications.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=13157. Last accessed on November 17, 2011.

> DoD pursue an initiative in protection materials by design that would make use of advanced computational and experimental methods.

During the course of the present study, President Obama announced the 10-year Materials Genome Initiative, a "new, multistakeholder effort to develop an infrastructure to accelerate advanced materials discovery and deployment in the United States."[45] The initiative is expected to "better leverage existing Federal investments through the use of computational capabilities, data management, and an integrated approach to materials science and engineering";[46] to advance ICME tool development significantly; and to provide a materials innovation infrastructure and work-force development. Development of ICME capabilities aimed at materials problems of pressing national importance is explicity included.

1.6.6 Other Reports on Simulation-Based Engineering

More recently, two additional relevant reports—the first, funded by the NSF, *Inventing a New America Through Discovery and Innovation in Science, Engineering and Medicine: A Vision for Research and Development in Simulation-Based Engineering and Science in the Next Decade,*"[47] and the second, from the National Science and Technology Council (NTSC), *Simulation-Based Engineering and Science for Discovery and Innovation*[48]—echo many of the findings and recommendations of the 2008 ICME report.[49] In the context of materials engineering and manufacturing, the reports cite success stories in which high-end manufacturers (including Goodyear, Ford, and Alcoa) employed computational modeling for product and process design, enabling reduced design cycle time and reduced costs associated with development, certification, and re-engineering while improving performance and efficiency. The reports also note that, in general, the simulation-based capabilities in materials science and engineering have lagged behind their counterparts in areas such as structural engineering, product design and weather and climate modeling. One of the consequences has been that the product design and development cycle now outpaces the materials development cycle by a significant margin, leading to a mismatch that hampers the insertion of new materials into engineering products. One of the related deficiencies identified in the reports is the lack of a comprehensive toolbox of validated physics-based material models that have the capabilities to span the pertinent range of time and length scales. The reports further emphasize the need to support education in simulation-based engineering and science across the entire age spectrum: from elementary, middle, and high schools to undergraduate and graduate university programs to continuing education for those practicing in the field.

1.6.7 Commonality in Recommendations of Previous Reports

Although each of the studies described was seemingly distinct from the others, the present committee was struck—as were the committees that produced some of the previous reports—by the similarities in the findings across the studies. However, it is often extremely difficult to attribute specific policy or procedural changes to individual report recommendations, especially as such changes may have resulted from multiple inputs and may occur years after a report is issued. The committee was also struck by the observations of those committees of the seeming lack of action in response to many of the previous report recommendations.

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[45] Office of Science and Technology Policy. 2011. "Materials Genome Initiative for Global Competitiveness." June. Available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf.

[46] Ibid.

[47] NSF. 2010. *Inventing a New America Through Discovery and Innovation in Science, Engineering and Medicine: A Vision for Research and Development in Simulation-Based Engineering and Science in the Next Decade.* Available at http://www.nsf.gov/mps/ResearchDirectionsWorkshop2010/RWD-color-FINAL-usletter_2010-07-16.pdf. Last accessed on November 11, 2011.

[48] NSTC. 2010. *Computational Materials Science and Chemistry: Accelerating Discovery and Innovation through Simulation-Based Engineering and Science.* Report of the Department of Energy Workshop on Computational Materials Science and Chemistry for Innovation. U.S. DOE, Office of Science. July 26-27. Available at http://science.energy.gov/~/media/bes/pdf/reports/files/cmsc_rpt.pdf.

[49] NRC. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12199.

One report, *Managing Materials for a Twenty-first Century Military*,[50] noted:

> While many earlier conclusions and recommendations made in one forum or another are similar to those developed by this committee . . . the [earlier] recommendations largely were never acted on or implemented.
>
> While high-level studies have been conducted for the DoD concerning future materials needs . . . it is not apparent to the committee that any effort has been made to incorporate the findings of these reports into materials planning processes.

Perhaps unsurprisingly, the recommendations emerging from the present study overlap significantly with some of those from previous studies. One exception is in the area of ICME, where significant action has coalesced. The findings of the present study further underscore the importance of ICME and provide specific context and recommendations with respect to lightweighting.

1.6.8 Systems Engineering

As noted in the 2008 NRC report *Pre-Milestone A and Early-Phase Systems Engineering: A Retrospective Review and Benefits for Future Air Force Systems Acquisition,*[51] it takes two to three times longer to move a weapons system from program initiation to system deployment than it did 30 years ago, and a common view is that better systems engineering (SE) could help shorten the time required for development. That study committee was tasked with examining the role that SE could play during the defense acquisition life-cycle, especially during the early period of concept development and refinement and analysis of alternatives.[52]

In Appendix B of that report, that committee developed a comprehensive definition and description of systems engineering. It also provided a "short version," as follows:

> The successful design, manufacture, and operation of . . . complex systems demands an engineering discipline capable of comprehending and managing all of their components and their interactions, and that discipline is systems engineering. Simply stated, SE is the translation of a user's needs into a definition of a system and its architecture through an iterative process that results in an effective system design. SE applies over the entire program life cycle, from concept development to final disposal.[53]

The committee stated that the use of formal systems engineering practices throughout the life cycle of an acquisition is critical to fielding the required system on time and within budget—but is especially important in the early, "pre-Milestone A" period. Steps such as "the consideration of alternative concepts (solutions) up front; the setting of clear, comprehensive key performance parameters and system requirements; and early attention to interfaces and interface complexity, to the concept of operations, and to the system verification approach" need to be completed before Milestone A and just after it. That committee found that "[a]ttention to a few critical systems engineering processes and functions, particularly during preparation for Milestones A and B, is essential to ensuring that Air Force acquisition programs deliver products on time and on budget."

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[50] NRC. 2008. *Managing Materials for a Twenty-first Century Military.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12028. Last accessed on November 17, 2011.

[51] NRC. 2008. *Pre-Milestone A and Early-Phase Systems Engineering: A Retrospective Review and Benefits for Future Air Force Systems Acquisition.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12065. Last accessed on November 17, 2011.

[52] According to *Defense Acquisitions: How DOD Acquires Weapon Systems and Recent Efforts to Reform the Process*, Congressional Research Service, April 23, 2010, "The rules governing the acquisition process are set forth in DOD Instruction (DODI) 5000.02, *Operation of the Defense Acquisition System.* As outlined in DODI 5000.02, the Defense Acquisition System uses 'milestones to oversee and manage acquisition programs. Each milestone has specific requirements. . . . A program must meet the specific statutory and regulatory requirements of a milestone in order to proceed to the next phase of the acquisition process.'" At Milestone A, a decision is made on whether a solution to a military need will enter the technology development phase. Activities that must take place before this point include analysis of alternatives and creation of a technology development strategy. Chapter 5 of this report discusses these milestones in more detail.

[53] NRC. 2008. *Pre-Milestone A and Early-Phase Systems Engineering: A Retrospective Review and Benefits for Future Air Force Systems Acquisition.* Washington, D.C.: The National Academies Press. P. 13. Available at http://www.nap.edu/catalog.php?record_id=12065. Last accessed on November 17, 2011.

This committee's approach is to take as a given that a systems engineering approach is critical—and that considering lightweighting early in the process is part of a comprehensive systems engineering approach.[54]

A follow-up to the Pre-Milestone A report was published in 2011. *Evaluation of U.S. Air Force Preacquisition Technology Development*[55] focused on the role of maturing technologies and inserting them at the appropriate time in the acquisition cycle. It provides additional evidence for the importance of systems engineering in technology development.

1.7 CONCLUDING REMARKS

Based on the results of earlier reports and the present study, it is evident that lightweighting offers enormous potential for improving the capabilities of military vehicles while simultaneously reducing energy consumption and the associated, burgeoning costs to the military. But the realization of such benefits requires not only the discovery and development of improved lightweight materials (those having high specific performance) but also, more critically, the use of systems-level design approaches that explicitly include lightweighting. Realizing the benefits of lightweighting will also require concerted, coordinated efforts of DoD agencies aimed at accelerating the materials design and development cycle and shortening the time required to field new technologies.

Strategic visions and investment strategies for defense-critical materials, modeling, systems engineering, and manufacturing also need to be formulated. Collectively, these efforts could help to revitalize U.S. manufacturing capabilities, with attendant economic benefits to the nation.

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[54] This report is not a comprehensive review of systems engineering. It uses terms such as "systems-level approaches" and "optimization" in the general sense of attending to the requirements of a system as a whole, subject to identified constraints. The committee recognizes that such usage may be imprecise. Please see the reports described and referred to in this section for more information.

[55] NRC. 2011. *Evaluation of U.S. Air Force Preacquisition Technology Development.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=13030. Last accessed on November 17.

2

Lightweighting Airborne Vehicles

2.1 CURRENT STATE OF LIGHTWEIGHTING IMPLEMENTATION AND METRICS

2.1.1 Drivers of Lightweighting

At the highest level, all aircraft designs are driven by performance, cost, and risk. The factors that affect each driver are these:

- *Performance:* thrust, weight, lift, and drag.
- *Cost:* research, development, test and evaluation (RDT&E); manufacturing; certification and qualification; and operations and support (O&S).
- *Risk:* safety, resource availability, technical maturity, and schedule.

Weight has been an important consideration in military and commercial aircraft design since the beginning of manned flight. It affects directly the amount of lift required to fly, which in turn affects the drag on the aircraft and therefore the thrust required to achieve the desired performance. Weight also has indirect impacts on the cost of the aircraft.

The importance of lightweighting for military aircraft depends on aircraft type. Table 2-1 relates the attributes shown previously in Table 1-1 to various military aircraft types. The three main attributes (functional capabilities, operational capabilities, and survivability) correspond roughly to the three parameters driving aircraft design as defined above (performance, cost, and risk), with some overlap. Trainers, fighters, and attack aircraft are included in the "fighter" category; primary military vehicles, tankers, and transports are included in "transports." "Primary" and "secondary" assess the relative importance of these capabilities for aircraft design, and the numbers 1 through 3 rank the importance of the attribute for the aircraft type.

Military aircraft are driven by performance features (functional capabilities), which are strongly affected by weight. The O&S attributes of fuel consumption, maintainability, and the like are still primary design drivers for most aircraft and are related to weight in a lesser sense by virtue of fuel consumption and efficiency of the design. Thus, weight considerations are central to aircraft design.

Survivability is a design parameter for all military aircraft but a primary driver only for fighters, which sometimes depend on low observability to get to the target. It is not so important for unmanned aerial vehicles (UAVs) and remotely piloted aircraft (RPA) because, at least to date, they are not being used for first-strike operations.

TABLE 2-1 Lightweighting Attributes for Military Aircraft Systems

Capability		Aircraft Type					Summary
General Attributes	Specific Attributes	Fighters	Transports and Bombers	Helicopters	RPA / UAVs	Commercial Transports	Aircraft (Tactical and Transport)
Performance	Speed Maneuverability Payload Range Effectiveness	Primary 1	Primary 1	Primary 1	Primary 1	Primary 2	Primary 1
Operational Supportability	Fuel Consumption Maintainability Durability Reliability Repairability	Secondary 3	Primary 2	Primary 2	Secondary 2	Primary 1	Primary 2
Survivability	Ballistic Impact Explosion Damage Tolerance Observability	Primary 2	Secondary 3	Secondary 3	Secondary 3	Secondary 3	Secondary 3

NOTE: RPA, remotely piloted aircraft; UAV, unmanned aerial vehicle.

However, at least two trends are forcing UAVs to become more reliable. When these aircraft begin to fly over populated areas, the potential for damage and injury to personnel on the ground when such aircraft fail in flight will be a concern. Moreover, the suite of sensors they carry is becoming increasingly expensive. UAV designers will need to begin paying as much attention to risk as designers of manned aircraft do. This risk tolerance must be traded off against the performance requirements for vehicles such as high-altitude, long-endurance (HALE) UAVs, where risk increases if design margins are reduced to achieve the lowest possible density, but flight over populated areas drives a desire for reduced risk. Generally speaking, lightweighting of military aircraft will therefore need to be done with an eye to retaining or improving survivability.

2.1.2 Historical and Current Lightweighting

Early work on composite and hybrid material systems in transport aircraft attempted to match their properties and design methods to those of aluminum. The results were nicknamed "black aluminum" structures, which ended up sacrificing many of the favorable characteristics of composites that had led to their adoption in the first place. For example, incorporating composites into structures originally designed for aluminum where transverse and shear stiffnesses had to be maintained meant that the tailored stiffness in bending of the composites could not be put to use.

Rotorcraft have also taken advantage of lightweight materials and structural concepts. Lightweight components for the engine and transmission housings have been studied but are not seeing widespread use today; however, lighter-weight materials and designs are finding their way into the airframe and the rotors of advanced rotorcraft.[1] Composites with integral stiffening were examined in the NASA/Army-sponsored Rotary Wing Structures Technol-

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[1] J.K. Sen and C.C. Dremann. 1985. "Design Development Tests for Composite Crashworthy Helicopter. Fuselage," *SAMPE Quarterly*, Vol. 17, No. 1, October, pp. 29-39.

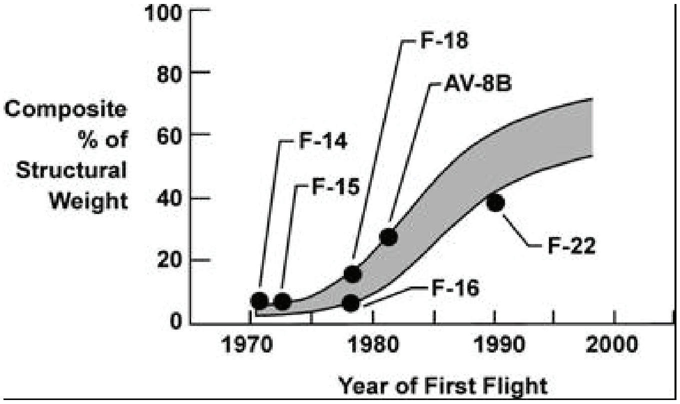

FIGURE 2-1 Composites in U.S. Fighter aircraft. SOURCE: C.E. Harris and M.A. Shuart. 2004. An Assessment of the State-of-the-Art in the Design and Manufacturing of Large Composite Structures for Aerospace Vehicles, NASA-Langley. Available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040086015_2004090422.pdf.

ogy Demonstration (RWSTD) program.[2] More recently, under Boeing funding[3] composite rotor blades have been developed that offer significant cost savings compared with those previously developed for the AH-64 Apache attack helicopter. Rotorcraft development organizations have been among the first to develop and employ health monitoring systems as a means to ensure the integrity of advanced composite systems.[4]

From 1970 to 2000, designers began to take advantage of the properties of resin matrix composites, which were introduced sequentially into the skins of the empennage (rear part or tail assembly), wings, and fuselages of military aircraft, as shown in Figure 2-1. After their successful implementation in military aircraft, these materials began to be introduced into commercial aircraft, as shown in Figure 2-2. Until recently, however, the cost of composite materials limited their application by commercial aircraft. Furthermore, the fuel savings that resulted from lighter weight were not sufficient to overcome the cost of the materials and the manufacturing processes.

In the 1990s, manufacturing technologies for composite materials became more capable, less costly, and more pervasive, allowing production of parts around the world. At the same time, higher actual and predicted fuel prices made composites increasingly desirable for commercial aircraft. By the time the Boeing 787 was being developed, the costs of design, production, and operation allowed much greater use of composites in the airframe. This was aided by the use of advanced physics-based modeling and simulation for design, development and manufacturing.[5]

As materials analysis and fabrication methods continue to improve, composite materials are being employed extensively, not just for lightweighting but also to improve impact resistance and resistance to fire, damage, lightning strikes, ultraviolet (UV) degradation, moisture, and thermal degradation. Over time, experience has led to the preference for certain resin systems and fiber-sizing materials. Repair methods have been developed for composite structures and have been successfully used in both commercial and military applications.

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[2] Shawn M. Walsh and Bruce K. Fink. 2001. "Achieving Low Cost Composite Processes through Intelligent Design and Control." Presented at the RTO AVT Specialists' Meeting, Low Cost Composite Structures, Loen, Norway. May 7-11. Published in RTO-MP-069(II).

[3] Jian Li, P.H. Jouin, and A.S. Llanos. 2010. "Durability and Damage Tolerance Enhancement Feature and Life Prediction Methodology for the Apache Composite Main Rotor Blade (CMRB) Root-end Fitting," American Helicopter Society 66th Annual Forum, Phoenix, Ariz., May 11-13.

[4] Michael L. Basehore and William Dickson. 1998. "HUMS Loads Monitoring and Damage Tolerance: An Operational Evaluation." Presented at the NATO RTO AVT Specialists Meeting, Exploitation of Structural Loads/Health Data for Reduced Life Cycle Costs, Brussels, Belgium, May 11-12. Published in RTO MP-7.

[5] Göran Fernlund. 2008. "Reduction of Risk and Uncertainty in Composites Processing Using Process Modeling and Bayesian Statistics." Presented at the 13th European Conference on Composite Materials, Stockholm Sweden, June. Available at http://www.escm.eu.org/ECCM13_broschure.pdf.

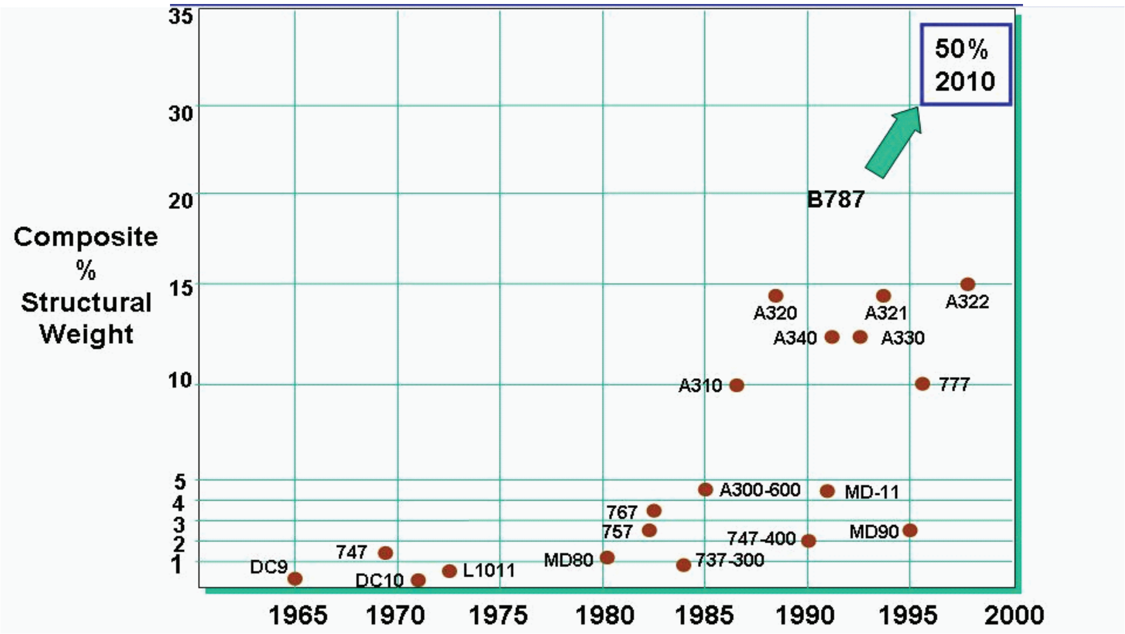

FIGURE 2-2 Composites in commercial transport aircraft. SOURCE: Charles E. Harris, James H. Starnes, Jr., and Mark J. Shuart. 2001. An Assessment of the State-of-the-Art in the Design and Manufacturing of Large Composite Structures for Aerospace Vehicles. NASA-Langley. Available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040086015_2004090422.pdf.

2.1.3 Current State of Metrics

Until recently, weight was used directly in calculating aircraft costs at the conceptual design stage. Military and commercial data dating back to 1935 had been used to develop and refine an understanding of the relationship between cost and weight for "built-up" aluminum structures. Translating weight into cost worked well until about 1970, when composite structures began to see greater application in military aircraft.[6]

Composite materials offer great potential for weight savings at the same time that they lead to improved performance for military aircraft and lower operating costs for commercial aircraft. However, metrics are not available to compare those benefits with the significantly increased production costs. The aluminum-based cost models are not valid for composites, and the uncertainty surrounding costs became greater in the late 1990s, when stealth materials were introduced in military aircraft such as the B-2 (Figure 2-3) to reduce radar signatures.

The higher costs of composites had less to do with raw material costs than with the need to fabricate parts in expensive autoclaves using tooling that was unique for each part and each design. Projecting the costs of aircraft that incorporated composite materials meant developing very detailed cost models that incorporated the cost of tooling and layup and reflected the complexity of the parts and of their fabrication. It has taken a long time for such tools to become standardized in the aerospace industry, and they still are not as well validated as the cost models for metallic structures had been.[7,8]

The assessment of risk is a crucial metric for advanced technology. Risk drives cost and schedule as program managers attempt to achieve the weight and cost advantages of advanced technologies while reducing the risk

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[6] K. Zhou, C. Radcliff, T. Lenzm, and J. Stricklen. 1999. "A Problem Solving Architecture for Virtual Prototyping in Metal to Polymer Composite Redesign," *Proceedings of the DETC'99: 1999 ASME Design Automation Conference.* September 12-15, Las Vegas, Nev.

[7] S.A. Reseter, J.C. Rogers, and R.W. Hess. 1991. "Advanced Airframe Structural Materials: A Primer and Cost Estimating Methodology." R-4016-AF. RAND.

[8] Han P. Bao, 2002. "Process Cost Modeling for Multidisciplinary Design Optimization." NASA Grant NAG-1-2195. Norfolk, Va.: Old Dominion University. June.

FIGURE 2-3 Composite applications for the B-2 highlighted the need for new validated cost models. SOURCE: Available at http://www.aviationexplorer.com/Stealth_Principles_What_Makes_Stealth_Aircraft_Work.html.

that technology maturation will lag, thus delaying the schedule and increasing the costs of implementation. While the relationship has been understood for a long time, only recently have tools become available that allow risk to have the same visibility as cost and performance (weight) in the manager's evaluations.

2.2 BARRIERS AND KEYS TO SUCCESS

Because aerospace applications, especially vertical lift vehicles like rockets and helicopters, can justify higher costs for materials that reduce their weight, cost is not as great a barrier as it is for land and sea applications. Developers will not seek to achieve lower weight without appropriate cost and risk assessments, but the more serious barriers to lightweighting in aircraft relate to technology and management. These barriers include the need for (1) new materials; (2) new manufacturing processes and equipment; (3) systems engineering approaches to handling the multiple demands placed on materials and structures by aircraft applications; (4) more rapid insertion processes that include advanced physics-based modeling and reduce the test burden; and (5) less risky transition methods that account for all the requirements of the new air vehicles.

2.2.1 Timelines for Materials Development

The development of composite material and of its associated manufacture take much longer than the design cycle for new systems.[9] As a result, manufacturers often use existing materials and manufacturing systems for which data exist rather than emerging materials and manufacturing systems that are promising but unproven.

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[9] C.R. Saff, G.D. Hahn, J.M. Griffith, R.L. Ingle, and K.M. Nelson. 2005. "Accelerated Insertion of Materials—Composites." 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference. April.

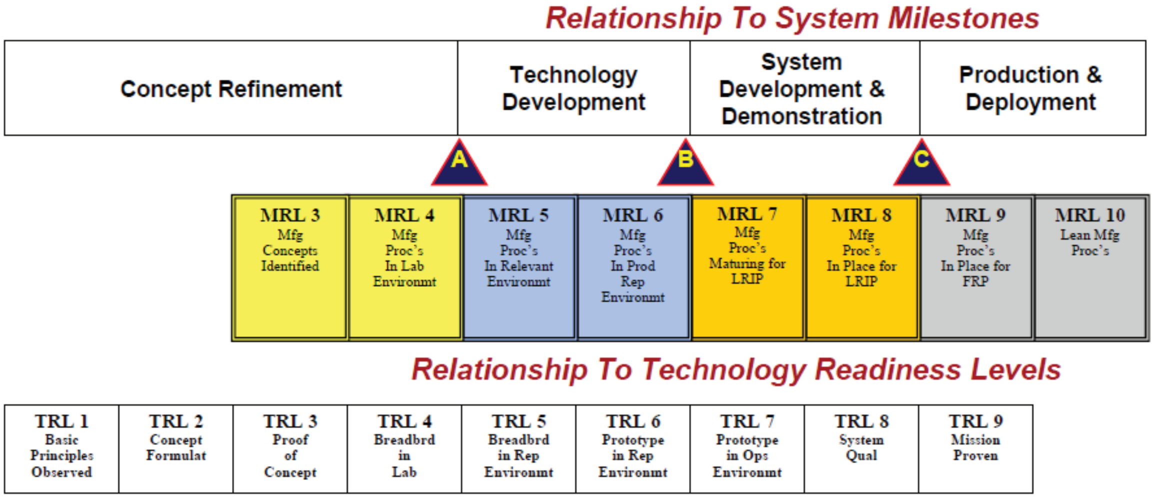

FIGURE 2-4 MRL relationships. SOURCE: Jim Morgan. 2006. "Manufacturing Readiness Levels (MRLs) for Multi-Dimensional Assessment of Technology Maturity," presented at the Air Force Research Laboratory Seminar/Workshop on Multi-Dimensional Assessment of Technology Maturity. Fairborn, Ohio. May 9-11. Available at http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA507087.

A material is considered application-ready at technology readiness level (TRL) 6,[10] when manufacturing scale-up and fabrication trials are complete and typical design values are in hand. The TRL scale measures the maturity of a technology's performance. The corresponding manufacturing scale of maturity is the manufacturing readiness level (MRL).[11] MRLs were developed to assess the manufacturing maturity of a technology or product and the plans for its future maturation; to provide a common language to convey risk; and to understand the manufacturing risk associated with producing a weapon system or transitioning a technology into a weapon system application. The relationship between TRLs and MRLs and system acquisition milestones is shown in Figure 2-4. System manufacturers can begin to consider a material during the conceptual and preliminary design phases, but once the product goes to detailed design, the materials must be locked in for that design unless special provisions are made to keep the door open. Even that must be curtailed at the engineering and manufacturing development stage, when testing for "allowables"[12] is done to develop data for materials in their as-fabricated condition for final design. (See the section "Materials Properties and Testing" in Chapter 1.)

Strong demand for lighter materials is driven by their performance payoff. As shown in Figure 2-5, each new composite material has been introduced gradually. As the materials and their manufacturing processes mature and their capabilities are demonstrated, they begin to account for a growing portion of each aircraft type. New materials are used first in hardware that is not flight-critical, then in empennage structures, then in wings (where their payoff is usually greatest) and in other primary structures (fuselage skins and substructures).

As shown in Figure 2-5, new materials are often first introduced in fighters, where performance is the main consideration, then in business jets and rotorcraft, then in the larger bombers, and, finally, in commercial aircraft. It takes 5 to 10 years from the availability of a new material to its introduction into aircraft empennage surfaces, depending on how quickly manufacturing processes can be developed that enable low-cost fabrication of parts;

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[10] See Chapter 5 of this report for a list of the DoD's nine TRL levels; level 9 is the successful use of a system in mission operations.

[11] *Manufacturing Readiness Level (MRL) Handbook, version 2.01*, July 2011. Available at http://www.dodmrl.com/MRL_Deskbook_V2.01.pdf provides best practices for MRL.

[12] "Design allowables are statistically determined material property values derived from test data. They are limits of stress, strain, or stiffness that are allowed for a specific material, configuration, application, and environmental condition." See p. 361 in *ASM Handbook,* Vol. 21, Composites, 2001. ASM International.

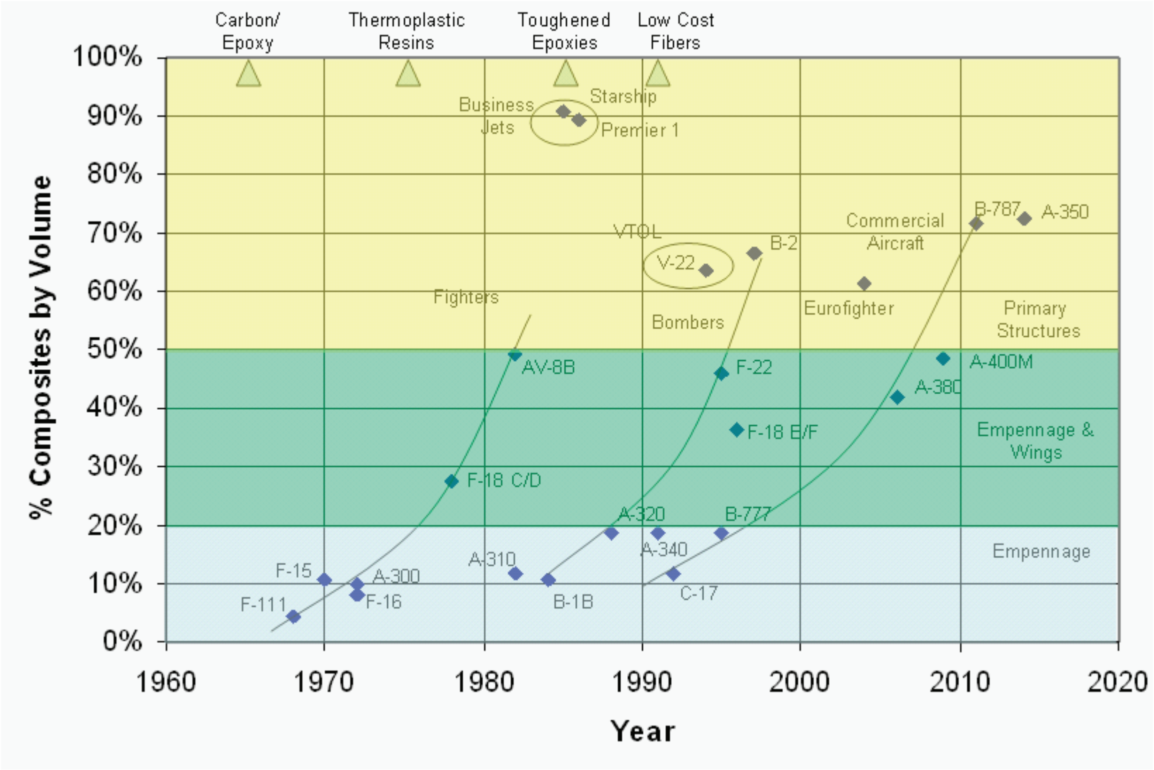

FIGURE 2-5 Timelines for the introduction of composite materials into aircraft. Of the two circles, the first links the business jets, and the second indicates the single rotorcraft to separate them from the other aircraft shown. SOURCE: Developed based on information in (1) R.B. Deo, J.H. Starnes, and R.C. Holtzwarth, “Low-Cost Composite Materials and Structures for Aircraft Applications,” paper presented at the RTO AVT Specialists’ Meeting on Low Cost Composite Structures, Loen, Norway, May 7-11, 2001, and published in RTO-MP-069(II); (2) M. Buckley, “An Introduction to Composites at Airbus,” presented at HYBRIDMAT 4, 2007, available at http://www.adcom.org.uk/downloads/3D Preform Technologies for Advanced Aerospace Structures.pdf; and (3) C. Harris and M. Shuart, “An Assessment of the State-of-the-Art in the Design and Manufacturing of Large Composite Structures for Aerospace Vehicles,” NASA Langley Research Center, April 2001. Available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040086015_2004090422.pdf.

about 10 years from fighters to bombers; and then another 10 years from bombers to commercial aircraft. The transition from empennage structures (tail surfaces) to primary structures is about 10 to 15 years.

2.2.2 System Engineering for Multifunctional Design

Multifunctional Structures

Components and structural elements that serve multiple functions offer the potential to lighten a structure. One way to achieve multifunctionality is through functionally graded materials that have properties and material constituents on one surface that differ from those on another surface, or are stratified through the interior of a part. There are a number of common examples, such as alclad aluminum, which provides corrosion protection for the base aluminum; or interlaminar toughened epoxies like those used in the 787, which provide impact damage resistance to composite systems. Hybrid materials like GLARE[13] that marry conventional aluminums with high-

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[13] R.C. Alderliesten. 2007. “On the Available Relevant Approaches for Fatigue Crack Propagation Prediction in Glare.” *International Journal of Fatigue*. Vol. 29, Issue 2, pp. 289-304.

strain glass-fiber-based systems can provide significant increases in damage tolerance for aluminum. The goal of graded materials has always been to build a material with graduated properties so that it meets different requirements in different locations within the material of component part.

Multifunctionality also encompasses "intelligent material" design, using either inherently smart materials or composites designed with multifunctional attributes. Examples of such materials are conductive polymers and high-temperature-resistant ceramic materials. Combinations of metallic and ceramic materials that protect the metal with a high temperature resistant coating while retaining the strength and toughness of the metal have been attempted for years. Similarly, inorganic and organic hybrid materials offer "designed" thermal and electrical conductivity and improved mechanical properties. While they have not yet reached maturity, nanoparticle technologies may offer the breakthrough required to make these kinds of materials a reality.

While progress has been made in the use of lightweight composites that are resistant to fire and tolerant of impact damage, there are other barriers to their use. Protection from electromagnetic effects (EME) is still an add-on system that is assumed not to carry loads, but because it strains along with the wing skin materials and has stiffness, it does carry a portion of the loads.[14] Burn-through criteria now set the minimum gage for composites more often than do the loads. That is, the time to burn through a composite fuselage skin panel can define the required thickness of the material. Thus, improving fiber, resin, or sizing materials is insufficient without also addressing burn-through.

To overcome these challenges to the use of composites, methods to predict their properties accurately will have to be developed. Testing will then be used not to characterize the materials, but to verify that they are behaving as predicted. The predictive capability cannot be limited to the simple geometries of the coupon and element tests—it must also be capable of predicting the performance of highly complex shapes, structures, and components not only under expected service conditions, but also under the worst case loading expected for off-nominal flight conditions.

Design for Durability

Today's aircraft structures must meet a host of durability requirements while still carrying loads and being capable of deflections that shed loads and enhance the aerodynamic performance of the aircraft. Durability issues include burn resistance, damage resistance, EME tolerance, and resistance to UV degradation, chemicals, moisture, and extreme temperatures. Aluminum is affordable and has an excellent set of properties under these conditions that, until recently, made it the material of choice for large transport aircraft.

Some successes have been achieved by a new approach to the design of structures such as wings, which would have not been possible with aluminum. For in-plane loads, composite laminates having more than 25 percent of the fibers running in the load-carrying direction have much greater resistance to fatigue damage than do metallic structures. Thus, good composite designs offer better durability than good metallic designs. Because composite materials allow for tailoring the twist of a wing as it bends under airflow, it has been possible to achieve better aerodynamic performance.[15] This tailoring has been used on X-29, F/A-18, and 787 aircraft to achieve better performance at lower weight. And only in recent years have the tools required to predict loads and perform these design and analyses been generally available to aircraft design teams.

2.2.3 Shorter Insertion Time for New Technologies

If allowables for composites must be determined based on testing, it would be beneficial to focus it on the means of the properties and not on their distributions, which take hundreds of tests to determine. The ability to predict strength based on material parameters such as resin make-up, fiber properties, sizing capabilities, variability of processing parameters, and so on might significantly reduce the amount of testing needed for composite materials. This is discussed further later in this chapter in the section on ICME for composite materials. One ele-

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[14] R. Jones. 1998. *Mechanics of Composite Materials*. 2nd Edition. Materials Science & Engineering Series.

[15] M.J. Patil. 1997. "Aeroelastic Tailoring of Composite Box Beams." Georgia Institute of Technology. Published through the American Institute of Aeronautics and Astronautics.

ment of the ICME approach is the Advanced Mean Value Algorithm,[16] which requires only 10 or fewer specimens to accurately determine the mean of the property distribution.[17] If the expected variation in properties is known from chemistry and mechanics, the allowables could be determined much more rapidly and from far fewer tests.

Another way of hastening the determination of allowables will be the development of semi-empirical approaches to predicting the strength of a composite material for a wide range of geometries, layups, and loadings. Today's methods for doing this are of two kinds. One is focused on using laminated plate theory[18] to convert the data from element tests to pseudo-lamina in situ properties, then applying them to structural strength predictions. This works well when the loads are applied in plane and when the damage state of concern is the same as that incorporated in the test. Whenever these conditions are violated, which happens all too often, additional tests are required to validate the more difficult details of the design. It can be very difficult for these tests to recreate the load or damage conditions of concern because the structure being modeled is so complex.

The second method[19] used is to intrinsically model the structure, including the layup, the geometry, the damage, and the loadings and perform a damage tolerance analysis on it. In general, this takes a very detailed finite element model, far more detailed than those normally used to predict internal load and strain distributions. Often because of the damage, loading, or geometry, these analyses must be performed using nonlinear methods, which increase run times and the complexity of interpretation. Such models cannot be run for every condition the aircraft might undergo: Because they are simply too complex and too time-consuming to validate and perform, they are run only for the most critical or complex cases.

A third possible way of surmounting the test barrier is to use existing tests and data to cover new materials, as was done using the Advanced General Aviation Transport Experiments (AGATE) process for general aviation vehicle design[20] and the Composite Materials Handbook 17 (CMH-17) methods for shared data.[21]

2.2.4 Accelerating the Transition from Laboratory to Product

The difficulty of bringing a new technology to the marketplace has been dubbed the Valley of Death, because so many promising technologies die before they are used in products. The Valley of Death occurs when technology is developed to some extent, and then a search begins for applications. Since the key requirements of candidate applications were not taken into account during the technology development process, oftentimes the development has to restart. Aircraft are no exception, and the difficulty of this transition inhibits the greater use of lightweighting technologies.

If technology is developed in response to a defined need, there is no Valley of Death. Therefore, the key to truly accelerating technology transition is to create a mechanism for technology pull. Advanced technology demonstrations (ATDs) are one strategy used by DARPA and the military services to provide the pull required to transition technology from the laboratory to deployable vehicles. Their purpose is "a demonstration of the maturity and potential of advanced technologies for enhanced military operational capability or cost effectiveness. ATD are identified, sponsored, and funded by Services and agencies."[22]

Here, DARPA has had a number of successes. However, the process is flawed when the prototype aircraft are given limited operational assignments after meeting only a few design requirements—i.e., before they are battlefield-ready. As described in the second part of Section 2.5.2, the Predator and Global Hawk Unmanned Aerial Vehicles were ATDs that were deployed in Iraq and Afghanistan. Their ability to persist over targets and deliver

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[16] Y.T. Wu, H.R. Millwater, and T.A. Cruse. 1990. "Advanced Probabilistic Structural Analysis Method for Implicit Performance Functions." *AIAA Journal*, Vol. 28, No. 9, pp. 1663-1669. September.

[17] E.J. Gumbel. 2004. *Statistics of Extremes*. Mineola, New York: Dover Publications.

[18] C. Kassapoglou. 2010. *Review of Classical Laminated Plate Theory*. Published online at http://onlinelibrary.wiley.com/doi/10.1002/9780470972700.ch3/summary.

[19] E.J. Gumbel. 2004. *Statistics of Extremes*, Mineola, New York: Dover Publications.

[20] For more information on the AGATE shared database process, see http://www.compositesworld.com/articles/agate-methodology-proves-its-worth. Last accessed October 19, 2011.

[21] For more information on composite properties, see http://www.compositesworld.com/columns/shared-composite-material-property-databases. Last accessed October 19, 2011.

[22] Information on ATDs is available at https://dap.dau.mil/glossary/pages/1414.aspx. Last accessed October 19, 2011.

small, accurate weapons was valuable to the war effort, but because of the limited design requirements, these UAVs failed to meet normal reliability and supportability goals typical for fielded aircraft.[23]

2.3 LIGHTWEIGHTING OPPORTUNITIES FOR AIRCRAFT

Although the aircraft industry has been seeking lightweight structures for more than 100 years, there are still a surprisingly large number of opportunities to reduce weight through exploiting emerging technologies to refine materials, manufacturing, design, and configuration.

2.3.1 Opportunities in Materials

It was recognized 20 years ago that high strain-to-failure graphite fibers would be relegated to research laboratories unless high strain-to-failure resins were developed simultaneously. Today, several promising materials could someday produce better, lighter structures.

Carbon Fiber Development

As shown in Figure 2-6, the use of carbon-fiber composites for lightweighting in commercial and military airplanes has grown since the early 1970s. The success of these composites illustrates the need for parallel development of a wide range of ancillary technologies (such as sizing [a chemical coating] for fibers, tooling for the system, and manufacturing processes for the application) and their eventual convergence.

These developments took many years, and each needed sustained support. For instance, although high-strength carbon fibers made from polyacrylonitrile (PAN) were first created in the 1960s by Aksanti in Japan and then in the Royal Aircraft Establishment (RAE) at Farnborough in 1963, the applications at that time, such as in sports equipment, were structurally non critical and did not take full advantage of fiber compositing. Similarly, the resins available early on in composite development had lower strain to failure than the fibers themselves, again limiting the performance capabilities of fiber composites. In parallel, successful implementation has also required extensive investments in the educational, industrial, and research infrastructures, both here and abroad.

The DARPA Advanced Structural Fiber program[24] seeks to increase fiber strength and stiffness by reducing defects in the fibers through advanced processing and by applying atomic control on a massive scale. Before such fibers can achieve meaningful weight savings, resins will need to be developed that can carry the fibers well and without microcracking.[25]

Each development related to composite materials has lent a capability for the aircraft. Durable epoxies have led to lightweight structures with high stiffness. Thermoplastics, while initially hard to fabricate, became an enabler for toughened systems that have allowed more damage tolerance. Thermoplastics have also provided better compatibility with high stiffness and strain fibers to enable very low thickness to chord wings for fighters and bombers. Eventually, low-cost fiber made it affordable to introduce composites into commercial aircraft. Chemistry- and physics-based analytical approaches of integrated computational materials engineering (ICME) are replacing much of the testing done in the 1980s and 1990s. These approaches could reduce the time it takes to put new multifunctional materials to work in aerospace applications.

Alternative Composite Polymers

Work in the 1980s showed that thermoplastic resins offered much higher durability than conventional epoxy resins. At that time, however, thermoplastic resins were comparatively expensive, sensitive to degradation when

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[23] E. Bone and C. Bolkholm. 2002. "Unmanned Aerial Vehicles: Background and Issues for Congress." Report for Congress, Order Code RL3187. April. Available at http://www.fas.org/irp/crs/RL31872.pdf.

[24] For information on DARPA's Advanced Structural Fiber program, see http://www.darpa.mil/Our_Work/DSO/Programs/Advanced_Structural_Fiber_(ASF).aspx. Last accessed October 19, 2011.

[25] H.G. Chae and S. Kumar. 2008. "Materials Science: Making Strong Fibers." *Science*, Vol. 319, Issue 5865, pp. 908-909.

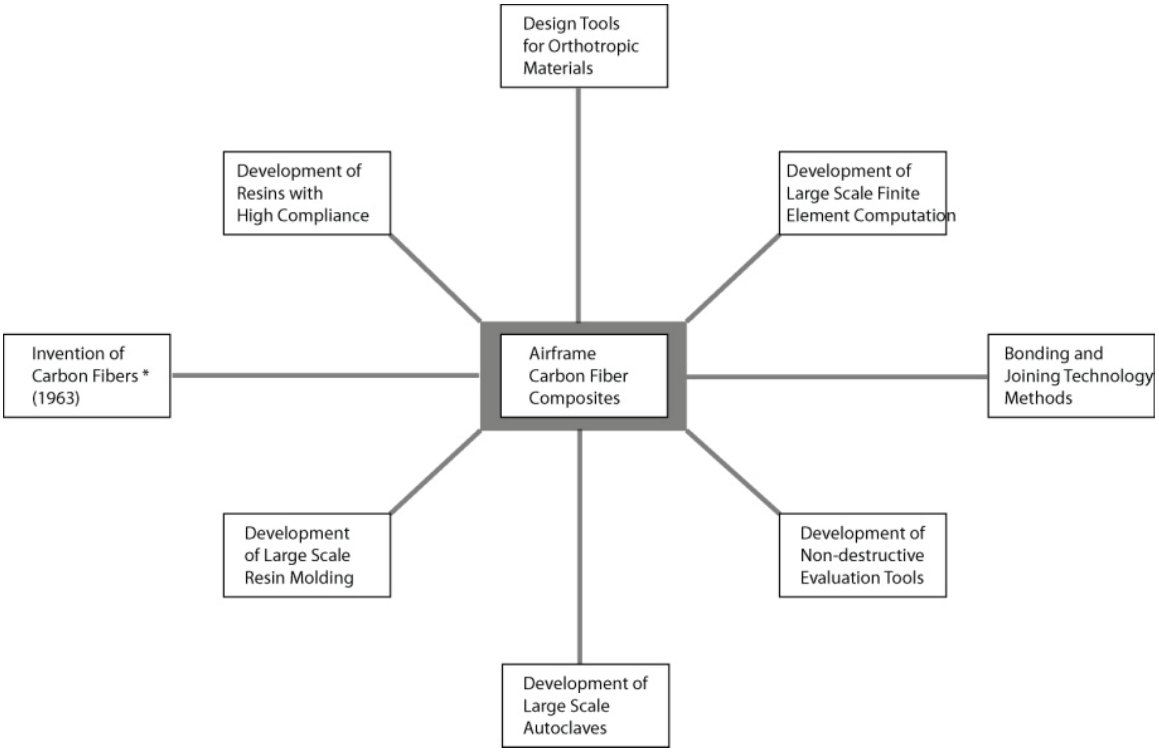

FIGURE 2-6 Multidisciplinary approach to carbon fiber development.

exposed to aircraft fluids, and difficult to work with because their processing takes place at very high temperatures. Instead of using thermoplastics outright, researchers used toughened epoxy resins to gain some of the strain-to-failure and toughness characteristics that the systems then lacked.

Today, pultrusion[26] and other ways of injecting thermoplastic resins into parts have progressed to the point where interest in such materials is growing. If these new processes overcome the barriers to the use of thermoplastics and are accompanied by new approaches to solvent sensitivity, the strain-to-failure, durability, and damage tolerance of thermoplastics could improve dramatically.

One of the main attractions of pultrusion is its simplicity of tooling and low labor requirements. At first glance, pultrusion appears to be a straightforward process: reinforcing fibers are saturated with a thermosetting resin matrix and pulled through a heated die, as shown in Figure 2-7. It turns out that successful pultrusion requires excellent control of the staging temperatures and the tension in the system, as well as control of the state of the material as it is pulled through the process in order to achieve the desired results. It is, in short, more of an art than it appears.

Nano- and Multifunctional Materials

Damage in aluminum—for example, cracks or dents—becomes evident before it limits structural performance. Less accessible areas inspected frequently enough to prevent cracks of critical size from forming.

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[26] Pultrusion is a continuous molding process for composite materials that mechanically aligns long strands of reinforcements for a composite material and then passes them through a bath of thermosetting resin. The coated strands are then assembled by a mechanical guide before the curing process. More recently, pultrusion has been used with thermoplastic matrices such as polybutylene terephthalate (PBT) either by impregnating the glass fiber with powder or surrounding it a sheet of the thermoplastic matrix, which is then heated to fuse the polymer and fibers. From "Putting It Together—the Science and Technology of Composite Materials." Australian Academy of Science. 2000. Available at http://www.science.org.au/nova/059/059glo.htm and http://www.acmanet.org/pic/products/description.htm.

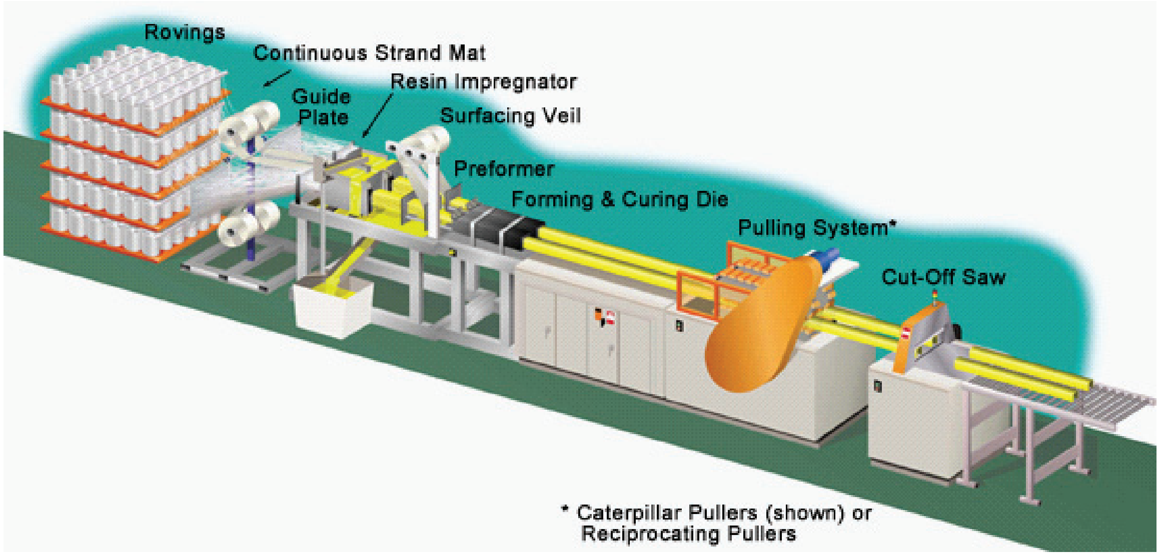

FIGURE 2-7 Pultrusion, a potentially simple process for manufacturing composites. SOURCE: Pultrusion Industry Council. Available at http://www.acmanet.org/pic/products/description.htm. Courtesy of Strongwell.

Impacts that would produce damage that could be easily seen on aluminum structures do not visibly damage the new composite structures.[27] Composites can delaminate internally after a low-impact load without any sign of delamination on the surface of the part. Designers of the Boeing 787 have gone a long way toward remedying this concern by using interply toughening and designs that accommodate large impacts without inducing damaging the structure. Research is also under way to explore the use of nanoparticles in the resin as one way of enhancing interply toughening.

An aluminum structure provides a second function: It serves as an electrical shield around the structure that conducts rather large currents without excessive heating or resistance. It forms a virtual Faraday cage around the structure that protects fuels from sparking and prevents lightning from entering the structure. Carbon fiber composites do not provide this function: Although carbon fibers conduct electricity, epoxy resins do not. The epoxy insulates the carbon from electrical sources, a composite structure must be shielded with another system to provide the same levels of spark and EME shielding that aluminum structures provide. Currently, EME shielding for composites is provided by add-on systems that are either placed on the skin or incorporated into the skin as woven wire. Use of carbon nanoparticles in the matrix resin is being explored as a mechanism to significantly increase the electrical conductivity of composites, particularly in out-of-plane directions. Successful design of these nanoreinforced materials could provide adequate EME shielding without the add-on wire mesh.

The potential improvement offered by nanotechnologies based on carbon nanoparticle enhancements to resins (Figure 2-8) has been proven at laboratory scale. However, this approach must be thoroughly explored and rigorously verified to ensure that it meets all of the aircraft's requirements. If the approach is successful, nanotechnologies could be used to create a single, multifunctional, integrated material system that improves on the damage resistance and EME protection that are today provided by multiple systems.

Hybrid Materials

Hybrid materials could provide some of the benefits of multifunctional materials at relatively low cost—lower even than the cost of composite materials. Hybrid materials, particularly metal-fiber laminates (shown in

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[27] Available at http://www.boeing.com/newairplane/787/design_highlights/.

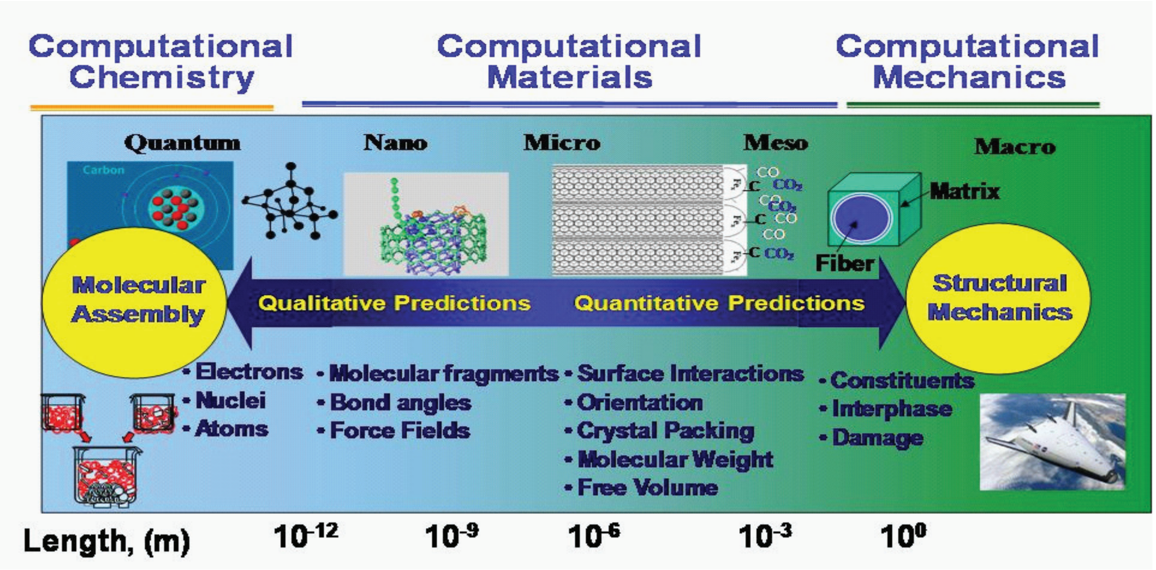

FIGURE 2-8 Multiscale modeling of nanocomposite materials. SOURCE: T.S. Gates, G.M. Odegard, S.J.V. Frankland, and T.C. Clancy. 2005. "Computational materials: Multi-scale Modeling and Simulation of Nanostructured Materials," *Composites Science and Technology,* Vol. 65, pp. 2416-2434. Reprinted with permission from Elsevier.

Figure 2-9), offer greater damage resistance than composites at half the cost. If cost or damage tolerance are large enough drivers to justify a weight penalty, hybrid materials can offer good damage resistance at an affordable price.

Airbus is using fiber-metal laminates and has invested heavily in bringing the technology to maturity and to a price that makes it affordable for its A-380. Whether that price will work for smaller aircraft is unknown. Hybrid materials offer some of the benefits of the multifunctional material systems, but not all. While GLARE and ARALL are commercial products, many others with different design drivers are being developed that promise still lower cost with very little penalty in other properties.

Metals with Improved Properties

Although composites offer the most potential for lightweighting, advanced metallic materials could also meet the needs of advanced vehicle applications, as shown in the example of a lightweight aluminum-lithium alloy in Section 2.5.2.

2.3.2 Opportunities in Manufacturing

Automated, Additive Manufacturing for Multifunctionality

Years ago, aircraft were almost entirely made from formed sheet products and were "built up" by fastening the products mechanically. Once high-speed machining became linked to digital design drawings, parts could be fabricated without the limitations of sheet products. More intricate substructures (e.g., bulkheads, spar, ribs, and frames) became possible that could perform more functions (carry loads, carry current, provide grounding for electronics, and so on) more efficiently than mechanically attached sheet products could do. The same advances were achieved for lightweight composite materials and structures, from hand-laid-up sheet skins and simple parts (doors, flaps, and so on) to more intricate resin-transfer-molded products for ribs, frames, and other structures. Composite materials provide benefits beyond lighter weight in that they are formed by "laying up" materials—

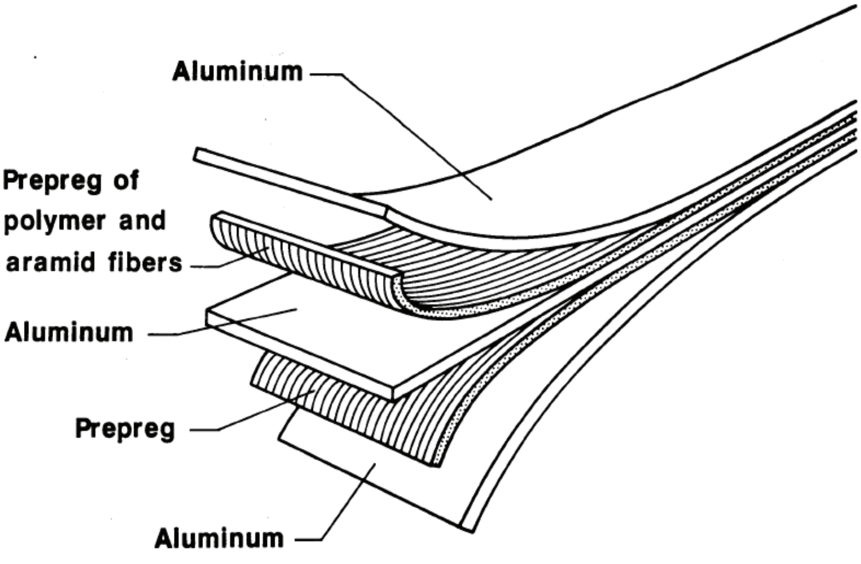

FIGURE 2-9 Hybrid fiber-metal laminates offer superior damage resistance. SOURCE: R.C. Alderliesten. 2005. *Fatigue Crack Propagation and Delamination Growth in Glare*. Delft, The Netherlands: Technical University of Delft Press.

that is, manufactured additively instead of by machining away materials, facilitating the design of materials for multifunctionality.

Recently, additive manufacturing techniques have been developed for metallic materials, notably aluminum and titanium. These techniques make it possible to go straight from the design to the fabrication of parts using systems very much like the three-dimensional printers that heat particles of material and lay them up using a laser to guide and fuse the particles. This technology allows the laying up of multiple materials, layer by layer, in particular locations so as to create specific properties and capabilities in at different places in the part. Maturation of this technology will likely create entirely new ways to design and fabricate multifunctional structures.[28]

The same additive manufacturing technology is potentially applicable to composite parts to permit the tailoring of properties at specific points to achieve multifunctionality. The technology imposes some constraints on the designs: For example, using a material of a given stiffness in one section of the part and a less stiff material in another section would cause distortion.

Non-traditional laminates that are not limited to 0°, +45°, –45°, and 90° plies but that may have other orientations to maximize the bending and twisting capability of the airfoil or the shear and pressure capability of a fuselage are now part of the design space made possible by new automated layup techniques. Fiber steering[29] to reduce strain concentrations is another capability made possible by these techniques.

Reducing the Number of Parts

The ability to produce large parts with complex geometries (such as curved spars) in composite materials would make it possible to have simpler structures requiring fewer fastened parts. Instead of kicks and joints in these structures, simpler joints could be used or perhaps none at all, as shown in Figure 2-10, where the substructures flow into one another seamlessly. However, the tools required to design and analyze such structures do not yet

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[28] "Rapid Technologies & Additive Manufacturing (RTAM)," Society of Manufacturing Engineers, 2011. Available at http://www.sme.org/cgi-bin/getsmepg.pl?/communities/rpa/rpahome.htm&&&SME&.

[29] Fiber steering is a method of constructing fiber-reinforced composites that allows the unidirectional fibers to be aligned along curvilinear paths. See "Fiber Steering for Laminated Composites," Adoptech. Available at http://www.adoptech.com/fibersteering/main.htm.

FIGURE 2-10 Airfoil manufactured as a single piece (no joints). SOURCE: Photo courtesy of BlueSwarf LLC, available at http://blueswarf.com/ProductCart/pc/viewContent.asp?idpage=150.

exist, and more experimentation is required to reduce the risk of this approach and to determine the capabilities that such structures might have.

Long, discontinuous fiber systems have been developed that offer the ability to drape and form parts with unidirectional properties in which the primary axes of the fiber can change radically without much loss in stiffness or strength. Simpler substructures seem to be on the verge of viability,[30] requiring only work to develop the capability to design and analyze them.

Larger Tools for Unitized and Integral Structures

Larger and more complex tooling is required to support the fabrication of larger and more complex shapes. Some of these tools have been demonstrated for prototype parts but are not durable enough for a production program that maintains the surface quality of the parts. Such tooling currently uses (low-cost) composite structures, thus averting mismatches between the coefficient of thermal expansion (CTE) of the tooling and that of the part being produced.

Bonding, Welding, and Fusing Assemblies

An alternative to larger, more complex tooling is to divide parts into smaller pieces and assemble them by bonding, welding, or fusion. Bonding was a method used more in the mid-20th century than today, although light aircraft with bonded structures have been flying for years. Of course, load intensities and strain levels have increased markedly in today's structures since that time and the properties required for bonds and weldments are near the limit of what can be produced. In addition, today's certification criteria require mechanisms to arrest bond delaminations, or redundant structures to carry loads, in case these joints fail without having given any outward sign of failure.

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[30] J. Pepin. 2011. "The Promise of Fiber Reinforced Thermoplastics: Pepin Associates' DiscoTex® Enables Lightweight, Recyclable Parts." Thomas News, Inc. June. Available at http://news.thomasnet.com/companystory/The-Promise-of-Fiber-Reinforced-Thermoplastics-Pepin-Associates-DiscoTex-Enables-Lightweight-Recyclable-Parts-847832.

Weldments have historically been assigned knockdown factors (i.e., a reduction in design value) to account for the effects of heat on the material in the weld. Friction stir welding has not eliminated heat-affected zones but has demonstrated the ability to provide near-pristine properties for them. There was some concern that the loss of corrosion inhibitors in a heat-affected zone might cause earlier corrosion in the weld, and testing has shown that the knockdown factor can be as high as 28 percent.[31,32] However, the strength knockdown factors are in about the same range as for specimens not having fatigue testing. Moreover, results in Europe discount this corrosion behavior.[33] Single-lap shear joints with double-pass welds show remarkable joint efficiency, far greater than any mechanical joints.[34]

High-Speed Precision Machining

Precision digitally driven machining has permitted significant weight reductions by reducing the minimum gages permitted by the manufacturing process. For example, years ago machining could provide only 0.04-in. thicknesses at the tolerances required for aerospace structures. The advent of high speed machining made it possible to maintain even closer tolerances and achieve a 0.02-in. minimum gage in places where frame members are lightly loaded. The weight savings afforded by these advances are almost free of cost, since digital process now routinely go from drawings to completed parts. The savings can amount to 5 percent of the overall structural weight.

2.3.3 Opportunities in Design

Trading Off Materials and Manufacturing Processes at the System Level

Product design currently begins with conceptual design at the system level. It defines the system, then the vehicle, then the assembly process, then the structure, and finally the parts. Materials and manufacturing methods are traded off against one another and defined at the part level. It is difficult to trade off materials and manufacturing processes at the point of conceptual design and system definition.

There are no clear metrics that link tradeoffs at lower levels to those at the vehicle or system level. Even though cost and weight are obviously traded off at the part level, determining the payoff of these tradeoffs at the system level requires weighting the payoffs throughout the system. The payoff is greater at the conceptual design stage, where weight savings can affect the overall size of the vehicle. Tradeoffs later in the design process at lower levels have much less effect if the size of the vehicle cannot be changed.

Multifunctional Parts

One of the best ways to achieve a lightweight vehicle is to ensure that as the substructure for a vehicle is being defined, no part is performing fewer than two functions. This approach represents a change in the focus of multidisciplinary design. For example, the structure can take loads and provide support for systems or support for doors. Bulkheads can support wings and still have the carry-through ability to carry loads under live fire. A structure may be able to perform three functions without additional weight—it may, for instance, carry fuselage loads, support a door, and carry electrical return currents.

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[31] Ibid.

[32] M. Czechowski. 2004. "Slow-Strain-Rate Stress Corrosion Testing of Friction Stir Welded Joints of Al-Mg Alloys." *Achievements in Mechanics and Materials Engineering*. 12th International Scientific Conference. Warsaw: Polish Academy of Science.

[33] J. Pepin. 2011. "The Promise of Fiber Reinforced Thermoplastics: Pepin Associates' DiscoTex® Enables Lightweight, Recyclable Parts." Thomas News, Inc. June. Available at http://news.thomasnet.com/companystory/The-Promise-of-Fiber-Reinforced-Thermoplastics-Pepin-Associates-DiscoTex-Enables-Lightweight-Recyclable-Parts-847832.

[34] L. Cederqvist and A. Reynolds. 2001. "Factors Affecting the Properties of Friction Stir Welded Aluminum Lap Joints." *Welding Journal*, Vol. 80, Issue 12, pp. 281S-287S.

Curved Parts

Early finite element routines and simplified analysis techniques dealt with structures in only two planes. Forming techniques, formed-in-place structures, and formable composites have made it possible to produce much more complicated structures that bend and turn through three dimensions that can be joined along straight load paths. This allows a structure to carry loads in the most efficient manner. Moreover, joints in simpler structures are easier to design, install, and maintain.

2.3.4 Opportunities in Configuration

Effects of New Materials and Manufacturing Processes on Configurations

An aircraft can be made lighter by changing the configuration itself. Not only can its size be changed, but also its shape. Many such reconfigurations have been successful—for example, the wings of the X-29, the nose of the 787, the shaping of the F-22 wing-to-body join, the lifting body, blended-wing X-45, and the blended-wing X-37 were all made possible by composite materials and the ability to fabricate them to carry loads and serve other functions. See Section 2.5.4.

Effects of Materials and Manufacturing on Configuration Tradeoffs

Manufacturing capabilities for composite and metallic parts are rapidly becoming more flexible. The question is whether these capabilities can be traded off at the conceptual design stage to decrease aircraft size and at the same time increase aircraft efficiency. Quantification of the tradeoffs is the goal of a current study at the Georgia Institute of Technology,[35] sponsored by Boeing. Researchers are developing systems-level metrics and ties to lower-level part definition parameters that could allow new manufacturing capabilities to be better exploited in new designs. After only a year, the project had already made significant progress in linking preliminary design parameters to lower-level metrics for materials and manufacturing processes.[36]

Reducing the Cost of Composite Materials

The Composites Affordability Initiative (CAI) was a joint project of the Air Force Research Laboratory, Office of Naval Research, and five aerospace companies that focused on reducing the risk of using advanced composite materials in aircraft. The program succeeded in lowering the cost of composite structures, which made greater weight reductions affordable, but it was not directly focused on lightweight materials or design. In fact, lighter weight often lost out to lower cost in the CAI program. The demonstration performed on a low cost wing for X-45C saved very little weight but cut the cost of the wing by 20 to 50 percent, primarily by reducing assembly time and using a bonded substructure approach.[37] The savings in cost and weight were demonstrated in the Air Force Research Laboratory (AFRL) Advanced Composite Cargo Aircraft (ACCA) program, which proved that in addition to the weight savings afforded by composites, “composite technologies are real game changers in reducing design and manufacturing costs and extending the life and reducing the maintenance costs over traditional metallic aircraft structures.”[38]

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[35] J. Ceisel and Z. Liu. 2008. “Manufacturing Influenced Design (MInD),” Aerospace Systems Design Laboratory. Atlanta: Georgia Institute of Technology. Available at http://www.asdl.gatech.edu/Advanced_Concepts.html.

[36] Z. Liu, P. Witte, J. Ceisel, and D. Mavris. 2011. “An Approach to Infuse Manufacturing Considerations into Aircraft Structural Design.” Technical paper, Society for the Advancement of Materials and Process Engineering (SAMPE), presented at SAMPE 2011, Long Beach, Calif. May.

[37] J. Russell. 2001. “Composites Affordability Initiative.” *AMMTIAC Quarterly,* Vol. 1, No. 3. Available at http://ammtiac.alionscience.com/pdf/AQV1N3_ART01.pdf.

[38] “Lockheed Martin Conducts Successful Flight of AFRL’s Advanced Composite Cargo Aircraft,” *PR Newswire*, June 2, 2009. Available at http://www.prnewswire.com/news-releases/lockheed-martin-conducts-successful-flight-of-afrls-advanced-composite-cargo-aircraft-61979512.html.

System-Level Metrics by Which Materials and Manufacturing Can Influence Configuration

Some of the metrics used in the Georgia Tech study—for example, part count, process steps, density, stiffness, and sizing—are not unique to the study. But some of them have provided surprises in the way they influence system-level metrics. For example, when initial composite designs that used isotropic composites were compared, it was found that these provided little or no benefit to the system on a cost for weight basis until quite a large number of aircraft had been assembled. This had always been believed to be the case, and the study has provided accurate, traceable cost and weight values that demonstrate it. The processes developed to weight metrics at the system level in order to trade off materials and manufacturing processes at that level have proven to be remarkably successful in forecasting capabilities, weight, and cost. The processes for weighting metrics also provide a measure of the risk inherent in new designs so that engineering managers can control the risk to acceptable levels.

2.4 LONG-TERM CHALLENGES IN LIGHTWEIGHTING AIRCRAFT

2.4.1 Identifying Future Threats and Their Implications for New Materials

Given the 10 years it takes to transition a material from the test tube to the point where its design properties have been demonstrated,[39] it is important that the Department of Defense (DoD) look at least 20 years into the future to define potential threats and identify the capabilities that might be needed to develop materials to counter those threats. Materials cannot be developed and matured within the typical 5-year aircraft development cycle and must be under development long before aircraft definition takes place. Moreover, even at the conceptual design phase, aircraft manufacturers cannot justify looking at materials that have no well-defined and demonstrated properties or manufacturing history behind them. New materials must be always in the pipeline where they are being refined to provide capabilities that mesh with the strategic needs of the armed forces.

The long timeline for materials development also underscores the need for integrated computational materials engineering (ICME) to bring the synthesis and fabrication of new resins into the digital age. Recent years have seen significant progress in understanding how different chemical structures affect the chemical, electrical, and mechanical properties of resins. Advances in computational chemistry may make it possible to design the molecular structure of the resin to meet structural and other requirements for a given application. The science of materials processing will be an integral part of this endeavor, ensuring that the desired section thicknesses and shapes can indeed be fabricated from the designer resins.

2.4.2 Incorporating New Materials and Manufacturing Processes in Conceptual Design Through Systems Engineering Approaches

Incorporating new materials and manufacturing processes in conceptual design calls for predicting the as-manufactured properties of these materials. Too often, laboratory-based properties have been used that do not match the as-manufactured properties of the material. It is here that computational materials engineering that accounts for processing at scale can help.

At the conceptual design stage, manufacturers are able to accept some risk as they consider new materials and technologies, but these must be within 2 or 3 years of maturity in order to be ready by the start of engineering, manufacture, and design definition.[40] Because this window of opportunity is so narrow, it is crucial that a suite of new materials and technologies ready for insertion into new designs be available. This readiness can be achieved only by sustained investment in candidate materials and manufacturing technologies.

This requires that materials, processing, tooling, and manufacturing all be part of the integrated product development team from conceptual design through detail design. Historically, these experts are brought into the

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[39] C.R. Saff, G.D. Hahn, J.M. Griffith, R.L, Ingle, and K.M. Nelson. 2005. "Accelerated Insertion of Materials—Composites." AIAA Paper 2005-2165. Available at http://pdf.aiaa.org/preview/CDReadyMSDM2005_970/PV2005_2165.pdf.

[40] Ibid.

team at the detailed design stage, but to enable them to have a positive impact on cost and schedule they should be on the team from the beginning of concept development.

As a design matures, manufacturers are less able to accept the risk of using unproven materials or processes. At preliminary design review (PDR), it is too costly and time-consuming to redesign the product and test the fall-back technologies to bring them to the level of maturity they must have for the later stages of development. Figure 2-11 shows this increasing risk as a function of the design cycle for aircraft. Note that once an aircraft is in production, its certification is based on the materials and processes used to manufacture it; the cost to switch materials in primary structures at that point is often far too high to justify the gains.

Conceptual design is the stage where a manufacturer investigates new materials and manufacturing concepts and determines their payoff for new designs. But decisions on materials and manufacturing processes at this stage are difficult because payoffs are determined at the part level, not at the vehicle level. Research is how to determine payoffs at the preliminary and conceptual design trades when the parts, and ultimately the components, have not yet been defined. Linking these part-level benefits to vehicle-level metrics is the focus of this research.

Often an optimized conceptual design presents a "mixed-material" solution in which one set of materials is used to achieve certain requirements and another material is used to meet other requirements. In an optimized design these materials obviously need to work hand-in-hand to meet all of the objectives. A mixed-material design increases complexity due to property discontinuities, leading to possible joining issues and the potential for corrosion. Also, available design software is incapable of modeling the behavior of mixed materials effectively, especially when they have different joint designs and bonds. An optimized systems design approach has to accommodate this complexity. The materials industry does not yet support this approach, so the application would likely be developed at the integrator. Development of tools that can support mixed-material solutions would aid the design and optimization process for lightweighting significantly.

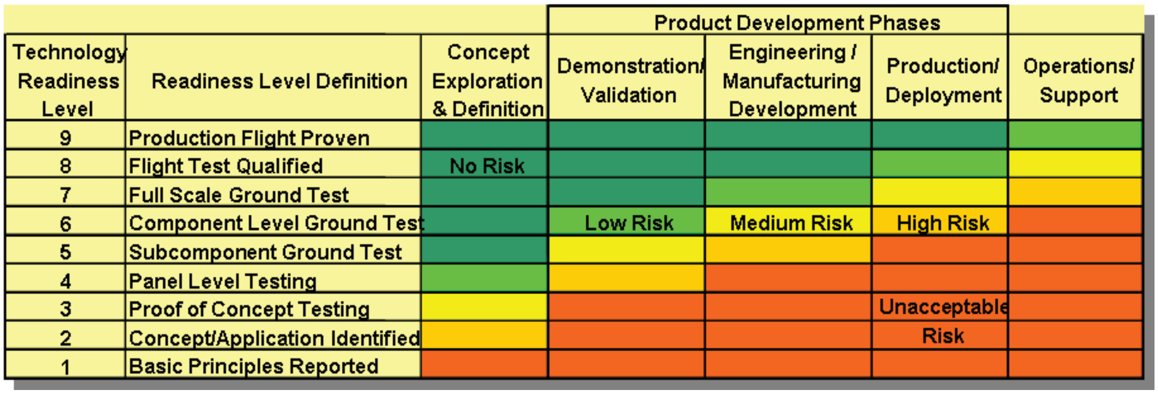
2.4.3 Accelerating Insertion by Reducing Testing Requirements for Composite Structures

Development of "allowables" for composite materials that may have a great variety of layups—and thus properties at any point in a structure—is crucial for effective design with such materials. In the past, designs had to meet strain cutoffs that were determined by the capabilities of the matrix. As matrix capabilities improved through toughening mechanisms, strain allowables were based on notched and damaged elements to ensure some level of damage tolerance in the structure. Allowables that include damage are very difficult to develop by test. Unlike for metallic structures, there are no proven, rapid methods to link the structural capabilities of undamaged composites to those of damaged composites. Although analysis methods for damage tolerance in composites have come a long way, there is still a long way to go before it will be possible to rapidly analyze and predict the behavior of composites under any given geometry, layup, or loading. Until this capability is developed, manufacturers will be forced to rely on extremely time-consuming testing of all composite configurations or fall back on more conservative (strain-limited) allowables. Research is needed to refine and further develop methodologies for analyzing progressive failure in different composite systems.

2.4.4 Application of ICME to Composite Materials

ICME, described in Chapter 1, could dramatically improve composite structural analysis in aircraft systems. Great progress is being made in applying ICME to develop materials for aircraft. Many first-level models to predict the behaviors of the today's materials have been developed, and some elements of ICME, such as chemical modeling of resins, are already being used to develop the materials needed for tomorrow. However, much more must be done to provide the rapid, accurate, and reliable prediction methods for composite materials that would reduce the enormous amount of testing required to design aircraft today.

The electrochemical modeling capabilities of the medical industry have been used and modified to accurately



			Product Development Phases			
Technology Readiness Level	Readiness Level Definition	Concept Exploration & Definition	Demonstration/ Validation	Engineering / Manufacturing Development	Production/ Deployment	Operations/ Support
9	Production Flight Proven					
8	Flight Test Qualified	No Risk				
7	Full Scale Ground Test					
6	Component Level Ground Test		Low Risk	Medium Risk	High Risk	
5	Subcomponent Ground Test					
4	Panel Level Testing					
3	Proof of Concept Testing				Unacceptable Risk	
2	Concept/Application Identified					
1	Basic Principles Reported					

FIGURE 2-11 Technical immaturity raises risk. SOURCE: C.R. Saff, G.D. Hahn, J.M. Griffith, R.L. Ingle, and K.M. Nelson. 2005. "Accelerated Insertion of Materials—Composites," AIAA Paper 2005-2165. Available at http://pdf.aiaa.org/preview/CDReadyMSDM2005_970/PV2005_2165.pdf.

capture the characteristics of the resin systems used in composites. The models can predict cure temperatures and the stiffness, toughness and strength of the resin systems, all of which facilitate the application of ICME.[41]

The processing of composite materials can be modeled to a degree—specifically, the interaction of tools with the composite laminates and parts can be examined. These models are used to assure good consolidation of the parts, as well as uniform heating and cooling rates to ensure that the part does not warp or warps only minimally when it is removed from the tool. The complex manufacturing plan of the 787 would not have been so successful without these tools.

Although the capability to apply these tools to predict the performance of composite materials is being worked on, the capability remains elusive. Today, industry still finds it difficult to predict composite performance from constituent properties. Designers must rely on semiempirical methods for predicting the strength of a laminated composite once its constituent properties are determined.

New analytical models are also needed to predict the strength of composites based on their geometry, layup, manufacturing processes, and damage condition. Such models would cut down on the number of tests needed to develop allowables so they are no more burdensome than the tests for metallic materials. Just being able to predict laminate strength properties from constituent materials would be a remarkable breakthrough in analysis capability. However, it is not a simple thing to accomplish: Industry has spent millions of dollars but made only a little headway.

2.4.5 Transition via Advanced Technology Demonstrations

ATDs must be developed using a systems engineering approach that takes into account all requirements (including those based on anticipated threats) for similar operational systems.[42] Determining requirements and defining them in terms of system performance requirements is the first step in any systems engineering approach to problem solving. Some past ATDs (see, in Section 2.5.1, Predator and Global Hawk) were promising but could not meet the warfighter's expectations when fielded. This shortcoming resulted from not having a clear a path from the early prototypes to a partly or fully operational vehicle.

There must be a clearly defined path to take what was initially demonstrated in the ATD and turn it into

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[41] Stephen Christensen, Andrea Browning, and Jon Gosse. 2011. "Computational Methods for New Materials Development: The 'Atoms to Airplanes' Concept." Presented at the 1st World Conference on ICME. Seven Springs, Pa. July. Available at http://www.programmaster.org/PM/PM.nsf/ApprovedAbstracts/643383E358B992ED852577D50083D5D1?OpenDocument.

[42] For more information on ATDs, see http://www.fas.org/man/dod-101/army/docs/astmp/c1/P1E2.htm. Accessed October 19, 2011.

a certified, operational system, making use of the ATD demonstration data to minimize the additional testing needed to certify the operational system. A good ATD begins with a fully defined set of operational requirements and objectives, designs the vehicle to meet those, and determines which of the requirements must be dropped for expediency and which functions will be demonstrated and which will not. At the conclusion of an ATD project there must be a plan to provide the functionalities missing in the demonstrator in future vehicles, first for limited operation and then for full operational capability.

2.5 EXAMPLES OF LIGHTWEIGHTING IN AIRBORNE VEHICLES

2.5.1 Unmanned Aerial Vehicles

Lightweighting in UAVs of All Sizes

The speed and weight of unmanned aerial vehicles (UAVs) cover a broad range, broader, in fact, than manned vehicles. They extend from hand-held micro-UAVs to large solar-powered loiter devices, to Mach 10 hypersonic vehicles, and on to vehicles as large as a 737.

These vehicles use lightweighting in very different ways. The Mach 10 X-43 scramjet (Figure 2-12) uses very high density materials to achieve high thermal gradients without thermal protection. Its air-breathing engine reduces weight by making it unnecessary to carry large oxidizer tanks, thus allowing a heavier payload or higher speeds. [43] High-altitude long-endurance (HALE) vehicles (Figure 2-13) use very low density materials because they have so little battery power with which to achieve very high altitudes and must sustain those high altitudes using solar power and batteries alone.[44] Even the tiniest aircraft, such as the bioinspired Delfly (Figure 2-14), must be kept very light—it weighs only 3 grams and extends 10 cm from wing tip to wing tip—in order to fly on a peanut-size power source.[45] Its flapping wings were modeled after dragonfly wings, which achieve stiffness and strength by being highly corrugated.[46] Other sources of ideas for making future UAVs lighter include developing a propulsion system based on automotive fuel cell technology[47] and emulating the lightweighting strategies of model airplanes.[48]

UAVs: A Variety of Lightweighting Techniques and Requirements

The smallest UAVs must be very lightweight in order to fly, and larger or faster UAVs use lightweighting for meeting various performance requirements. Strategies under development have included air breathing engines, solar power, adaptation of automotive fuel cells, model airplanes, UAV wings based on insect wings, and others.

Deployment of Predator and Global Hawk from Advanced Technology Demonstration Program

The unmanned aerial vehicles (UAVs), Predator and Global Hawk, were deployed in Iraq and Afghanistan after being designed and validated through the ATD program. The foreshortened requirements of ATDs demonstrate the capability of the platform but omit testing with respect to the specific battlefield requirements and usage to

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[43] "X-43A raises the Bar to Mach 9.6," *NASA News,* Sept. 2, 2010. Available at http://www.nasa.gov/missions/research/x43-main.html; A. Brown, "X-43A Captive Flight Succeeds, Air Launch Next," *NASA Dryden Research Center X-Press,* Vol. 48, Issue 8, Sept. 30, 2004.

[44] "Helios Prototype Solar-Powered Aircraft," NASA Dryden History, Nov. 3, 2009. Available at http://www.nasa.gov/centers/dryden/history/pastprojects/Helios/index.html.

[45] G.C.H.E. de Croon, K.M.E. de Clerq, R. Ruijsink, B. Remes, and C. de Wagter. 2009. "Design, Aerodynamics, and Vision-Based Control of the DelFly." *International Journal of Micro Air Vehicles*, Vol. 1, No. 2, pp. 71-97.

[46] S.R. Jongerius and D. Lentink. 2010. "Structural Analysis of a Dragonfly Wing." *Experimental Mechanics*. Vol. 50, No. 9, pp. 1323-1334. Oct. 26. Available at http://www.delfly.nl/Jongerius%20and%20Lentink%202010%20Dragonfly.pdf.

[47] J.R. Wilson. 2003. "UAVS: A Worldwide Roundup." *Aerospace America,* June. Available at http://www.aiaa.org/aerospace/Article.cfm?issuetocid=365.

[48] A. Noth, W. Engel, and R. Siegwart. 2006. "Design of an Ultra-Lightweight Autonomous Solar Airplane for Continuous Flight." Available at http://infoscience.epfl.ch/record/97588/files/FSR05_Sky-Sailor.pdf.

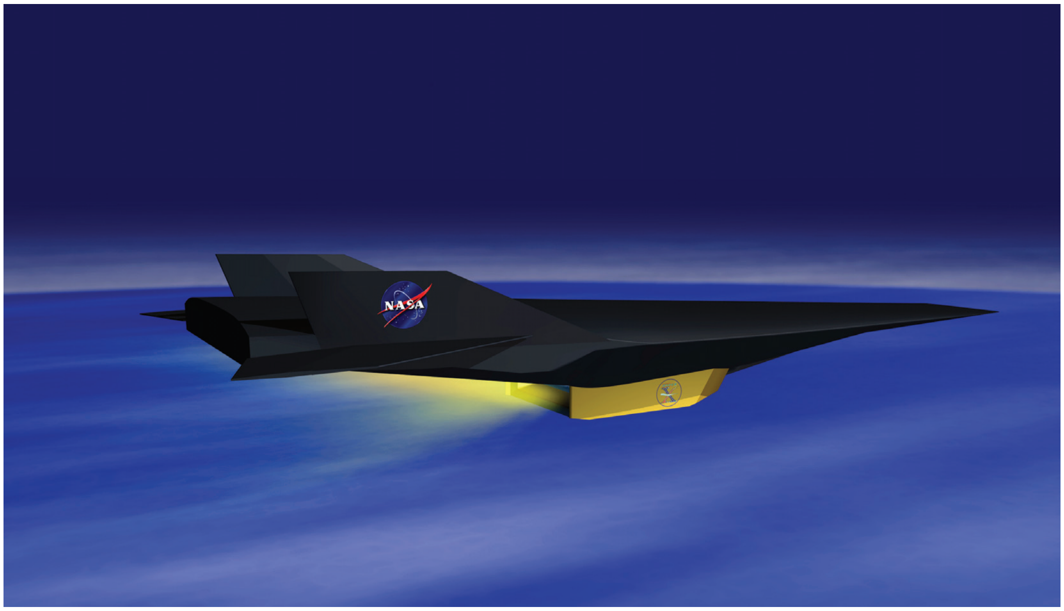

FIGURE 2-12 X-43A Scramjet after separation from Pegasus booster. SOURCE: NASA Dryden Research Center Photo Collection, available at http://www.dfrc.nasa.gov/Gallery/Photo/X-43A/Large/ED04-0082-4.jpg.

ATDs: Adequate Testing with Rapid Transition to Production

The problems with the Predator and Global Hawk on the battlefield suggest that more testing of ATDs could improve battlefield readiness. However, the performance of these UAVs also shows that the ATD program is, on balance, an effective way to deploy systems with new capabilities.

which they would be exposed. Now that these UAVs are fielded, limitations in their design capabilities with respect to battlefield needs are becoming apparent. Still, their ability to persist over targets and deliver small, accurate weapons to minimize collateral damage have been valuable, and these capabilities more than compensate for their shortcomings (e.g., performance problems under varying weather conditions).

2.5.2 Super Lightweight Tank for the Space Shuttle, using Aluminum-Lithium

To place the International Space Station modules in orbit, the weight of the space shuttle had to be significantly reduced.[49] The successful development of a new super lightweight tank (SLWT) to replace the lightweight tank (LWT) provided 50 percent of the performance increase required for the shuttles to reach the International Space Station.

The weight reduction achieved was made possible by the development of the 2195 aluminum-lithium alloy. When work on the new alloy began, there was a strong bias against aluminum-lithium (Al-Li) alloys because the previous generation of aluminum-lithium alloys (2090 and 8090) had demonstrated poor fracture toughness. This toughness issue was overcome by a new formulation and new processing technologies. This produced an alloy—Al-Li 2195—with improved properties and a lower density than the 2219 alloy previously used for the external tank of the shuttles and reduced the weight of the external tank by 7,500 lb (3,402 kilograms). For comparison, the SLWT weighs 36,123 lb, the LWT weighs 43,623 lb, and a Standard Weight Tank weighs 52,589 lb.

The lithium in Al-Li 2195 made the initial welds of the external tank far more complex. The repair welds

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[49] For more information, see "Analysis of International Space Station Vehicle Materials on MISSE 6," available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100033233_2010034433.pdf. Last accessed October 19, 2011.

FIGURE 2-13 NASA's HELIOS, a type of high-altitude long endurance (HALE) vehicle. SOURCE: NASA Dryden Research Center Photo Collection, available at http://www.nasa.gov/centers/dryden/images/content/105841main_helios.jpg.

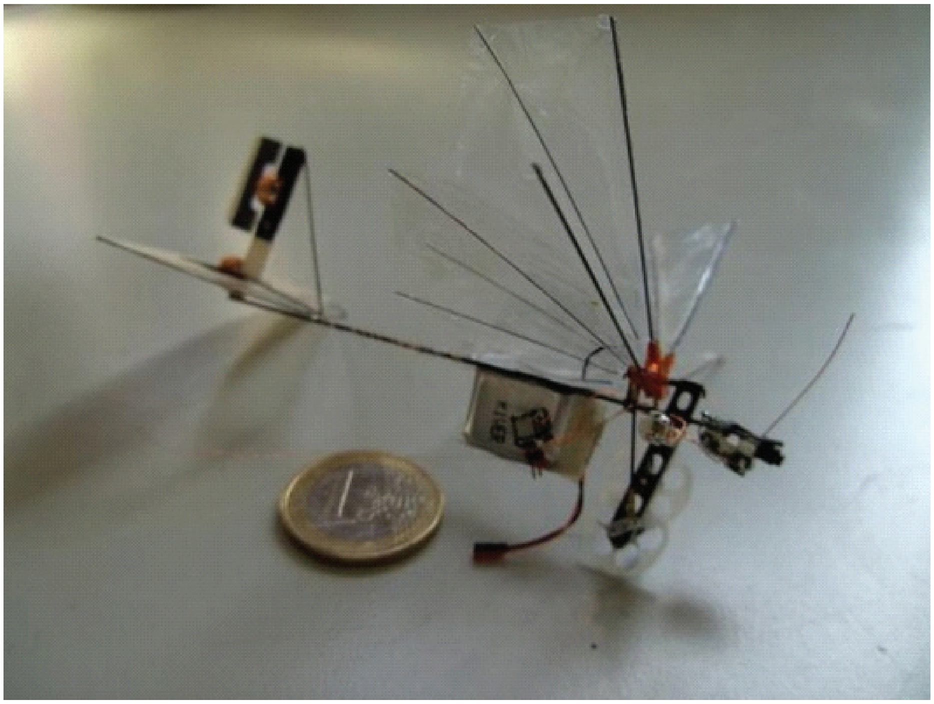

FIGURE 2-14 TU delft–Delfly. SOURCE: Used with permission of www.DelFly.nl; available at http://www.delfly.nl/?site=Publications &menu=&lang=en.

were difficult to make and the joints in the external tank had much lower strengths. In an effort to mitigate the increased production cost and regain the mechanical properties of the earlier Al 2219 external tank, the project began researching alternative welding techniques. The friction stir welding process produces a joint stronger than the fusion arc welded joint and has only three process variables to control: rotation speed, travel speed, and pressure, all of which are easily controlled. The fusion weld, in contrast, has to control many process factors, such as purge gas, voltage and amperage, wire feed, travel speed, shield gas, and arc gap. The increase in joint strength, combined with the reduction in process variability, provides an increased safety margin and a high degree of reliability for the external tank. Shuttle external tank weights are compared in Table 2-2.

The successful development of aluminum lithium 2195 illustrates what can be accomplished when fundamental alloy development is integrated with processing and design. The addition of Ag to the alloy promoted a distribution of the T1 phase in the microstructure that gave good transverse strength, which had been the weak strength direction in earlier generation Al-Li alloys 2090 and 8090. Solving the transverse strength problem allowed this alloy to be used to fabricate section thicknesses required for the shuttle external tank. Friction stir welding also contributed to the success of this allocation as noted above.

SLWT: New Materials and Processes Go Hand in Hand

Advanced processing methods must often be used for the advanced materials used for lightweighting. When fundamental alloy development, advanced processing, and design are addressed together, it allows consideration of tradeoffs and thereby improves the final design.

2.5.3 Using Aeroelastic Tailoring of Composite Wings to Enable Higher Maneuverability

X-29 Wings

The thin forward swept wing of NASA's X-29 (Figure 2-15) can be achieved only with tailored composite wing skins. Such a wing improves maneuvering performance because the ailerons are not "washed out" by wing bending at high angles of attack as they are on rear swept wings. The wings still provide the sweep required to achieve supersonic flight.

The composite wings of the X-29 were designed to achieve flutter-free flight in the forward swept configuration. "State-of-the-art composites permit aeroelastic tailoring, which allows the wings some bending but limits twisting and eliminates structural divergence within the flight envelope (i.e., deformation of the wing or breaking off in flight)."[50]

X-29, F/A-18, 787: Advantages to Composite Wings

Composites offer bending torsion relationships that allow tailoring wing bending to achieve lightweight designs with better performance. The significant laminate tailoring to achieve the necessary stiffness in torsion offers performance characteristics that cannot be achieved any other way.

FA-18 E/F Wings

The FA-18 E/F is a much larger aircraft than its predecessor, the FA-18 C/D. Its larger size was enabled by IM-7 fibers and the toughened resin systems required to exploit the additional strain and strength capability of those fibers (without being limited by resin strains to failure). The toughened resin allowed the strengths after impact damage to remain near those of open holes and thus not drive the design to an overly conservative strain level. The additional stiffness of the fibers made an expanded wing planform possible without a comparable increase

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[50] Federation of American Scientists. 2010. "The X-29." Website of the Federation of American Scientists. Available at http://www.fas.org/programs/ssp/man/uswpns/air/xplanes/x29.html. Last accessed December 7, 2011.

TABLE 2-2 Space Shuttle External Tank Weights

		Weight (lb)		
Component		Standard Weight Tank	Lightweight Tank[a]	Super Lightweight Tank[b]
1	Structure (LO_2 and LH_2 tanks, intertank)	52,589	43,623	36,123
2	Thermal protection (external foam, misc.)	5,959	4,823	4,823
3	Propulsion (feed, vent, pressure systems)	2,951	2,951	2,951
4	Power (cables, supports)	372	372	372
5	Controls	0	0	0
6	Avionics (instrumentation and supports)	68	68	68
7	Environment	0	0	0
8	Other (orb., SRB attachment, misc.)	6,676	5,954	5,954
9	Growth	0	0	0
10	Non-cargo (unusable and reserve LO_2 and LH_2)	8,209	8,209	8,209
	TOTAL	76,824	66,000	58,500

[a] Weight reduction made in structure and SRB attachments.

[b] Replace major portion of Al2219 components in lightweight tank with Li Al 2195 alloy.

SOURCE: Prepared with information in the NASA paper “Super Lightweight Tank—A Risk Management Case Study in Mass Reduction.” Available at http://www.nasa.gov/externalflash/irkm-slwt/Text%20Case/SLWT%20RM%20Case%20Study%20Accessible%20Version.pdf.

in wing thickness. The fibers also provided enough outer wing torsional stiffness to maintain the aerodynamic shaping of the very thin wing.

787 Wings

The Boeing 787 uses composites to tailor its wings, allowing much more efficient cruise flight than had been possible with the earlier metallic wings. These tailored wings, which have raked wing tips, have been designed to optimize cruise performance, and they bend more than conventional wings. To maintain torsional stiffness for the outer wings and still provide the required bending stiffness, such a wing has a highly tailored layup along its span.

2.5.4 Commercial Aircraft Applications

Extensive Use of Composites in the Boeing 787

The Boeing 787 (Figure 2-16) is the first commercial plane to have a composite fuselage. Composites were selected primarily to reduce weight, and the design offered significant weight savings. However, Boeing added weight back to the design to address lightning, noise, and manufacturing issues. The weight breakdown for the 787 aircraft is shown in Figure 2-17.

For large commercial aircraft, small differences in weight add up quickly—for example, a reduction of only 5 lb per floor beam makes it possible to carry an additional 250-lb passenger. The revenue added by one additional passenger over the life of the vehicle is equivalent to between 0.5 and 0.3 percent of the value of the vehicle.

While composites account for 50 percent by weight in the 787, the low density of these materials means that the amount of composite material by

787: Challenges of Large Composite Platforms

Large-scale application of composites remains a new and difficult undertaking. Boeing’s breakthrough use of composites for the fuselage reduced weight but suggests that multifunctionality could have retained more of the lightweighting benefits of a large composite platform.

FIGURE 2-15 X-29 aircraft, featuring forward-swept wings. SOURCE: NASA Dryden Flight Center Photo Collection, available at http://www.nasa.gov/centers/dryden/images/content.

volume is about 72 percent.[51] Not only does the move to composites reduce weight, but going to one-piece barrel sections with integral stiffeners (see Figure 2-18) also reduces the number of fasteners required to produce the aircraft by roughly 50,000. These advances, combined with fuel-efficient and lighter engines, electronic systems in place of hydraulic systems, and a myriad of lesser weight-reducing technologies, make the 787 capable of flying more people longer distances with lower fuel consumption than any other airliner in the world.

Weight determines the range of commercial aircraft and therefore the city pairs that can be served. A paper by Bernstein Research[52] looked at Airbus estimates of the reduction in 787 range based on its estimates of 787 overweight condition. The assessment estimates that a 15,000-20,000 lb overweight condition will degrade the performance of the 787 "into a range near 6,900 nm, well below the promised 7,700-8,200 nm range." Boeing states in the same article that early 787s will be overweight but that the company is making every effort to restore the promised performance. Composites helped with lightweighting, but the large scale of the composite structure encouraged a conservative design, with the result that so far the 787 has achieved only about half of the anticipated weight reduction.

Advanced Materials for the Airbus A350

Weight has so much value for the commercial aircraft customer that Airbus was forced by its customer base to move from a hybrid metallic/composite baseline fuselage to an all-composite baseline fuselage. Design changes like these become tremendously expensive when the time and effort that goes into engineering, design and certification testing are taken into account. Because of the uncertainty surrounding today's design and analysis methods for these material systems, much of the certification readiness testing must be carried out using large components

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[51] Justin Hale. 2006. "787 from the Ground Up." *Aeromagazine,* Quarter 4, pp. 16-23. The Boeing Company.

[52] Jon Ostrower. 2009. "Analysis: 787-8 Weight Examined (Update 1 with Boeing Comment)." Bernstein Research. May.

FIGURE 2-16 Boeing 787, a primarily composite commercial airliner. SOURCE: Boeing.

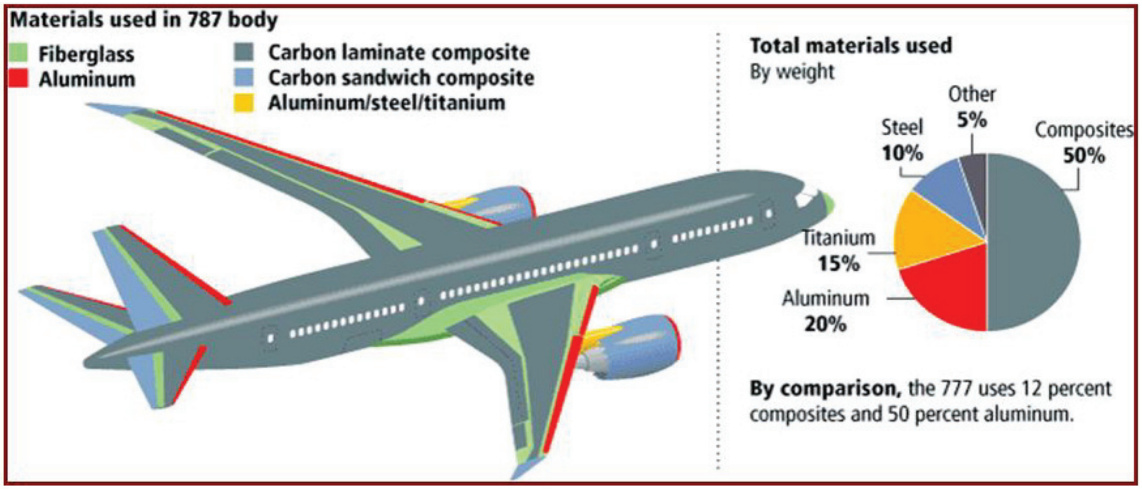

FIGURE 2-17 Boeing 787, which uses approximately 50 percent structural composites by weight. SOURCE: Boeing.

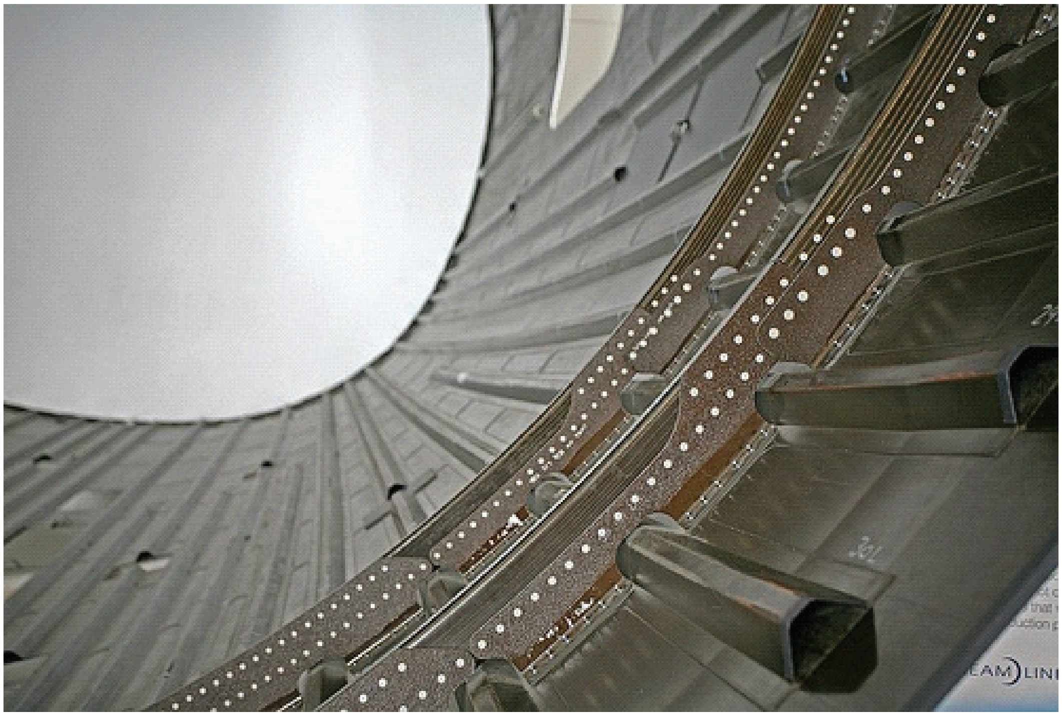

FIGURE 2-18 787 composite fuselage structures. SOURCE: Justin Hale. 2006. “787 from the Ground Up.” *Aeromagazine***.** The Boeing Company, Quarter 4. Pp. 16-23.

like the barrel shown for the XWB A350 fuselage in Figure 2-19.

A350: Uncertainty in Design and Analysis Tools

Weight- and performance-conscious commercial aircraft will continue the shift to composite fuselages, but design and analysis tools have not yet caught up to the need. The design process requires development and validation of more accurate and comprehensive design and analysis tools to realize the full potential of lightweighting of structures with composite materials.

2.5.5 Composite Crew Module for the ARES I Launch Vehicle

Under the Constellation program, NASA devoted considerable resources to reduce costs and lighten payloads through increased use of composites in future space structures. In 2006, the NASA Engineering and Safety Center studied the feasibility of a composite crew module (CCM) for the Constellation program crew exploration vehicle. Constructing a CCM was found to be feasible, but a detailed design would be necessary to quantify technical characteristics, particularly in the areas of mass and manufacturability.

The CCM project was chartered in January 2007 as a partnership between NASA and industry that shared design, manufacturing, and tooling expertise.[53] The project’s goals were not only to deliver a full-scale test article 18 months after project initiation but also to develop a network of NASA engineers with hands-on experience using structural composites in complex spacecraft design.

The CCM was based on the architecture of Orion’s aluminum crew module. The design for the CCM con-

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[53] C. Collier, P. Yarrington, M. Pickenheim, B. Bednarcyk, and J. Jeans. 2008. “Analysis Methods Used on the NASA Composite Crew Module.” American Institute of Aeronautics and Astronautics. Available at http://hypersizer.com/pdf/AIAApaperCollierCCM107727.pdf.

FIGURE 2-19 Test fuselage section for the Airbus A350 XWB aircraft. SOURCE: Airbus.

Ares I: Composites Improve Launch Vehicle Performance

Composite construction can be used to lightweight very large platforms and can prepare a cadre of engineers to apply that experience in future projects.

sists of "a stiffened honeycomb sandwich, with carbon fiber/epoxy skins and aluminum honeycomb core."[54] Fiber SIM software calculated the shape and size of each ply segment to conform to the tooling and then exported that information to a numerically controlled cutting machine.

One unique feature of the CCM design is the structural integration of the packaging backbone with the floor and pressure shell walls (Figure 2-20). This design provides a load path that accommodates load sharing with the heat shield, especially for water landing load cases. Another unique feature of the composite design is the use of lobes between the webs of the backbone. This feature puts the floor into a membrane-type loading, resulting in a lower mass solution. Connecting the floor to the backbone and placing lobes into the floor resulted in mass savings of approximately 150 lb for the overall primary structure.[55]

As the design progressed and analysis became more mature, analyses were divided into three classes:

- Analysis for optimization of sizing (a chemical coating), which included architectural trade studies, optimum honeycomb sandwich design, and optimum composite layups;
- Analysis for failure margins of safety for large sheets of material, which included panel buckling, composite strength failure, and damage tolerance, and sandwich-specific facesheet wrinkling and core shear, and

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[54] Sara Black. 2009. "Simulation Simplifies Fabrication of All-Composite Crew Module." *High-Performance Composites.* November. Available at http://www.compositesworld.com/articles/simulation-simplifies-fabrication-of-all-composite-crew-module.

[55] NASA Engineering and Safety Center. 2008. "Technical Update." Available at http://www.nasa.gov/pdf/ 346545mainNESC08TechUpweb.pdf.

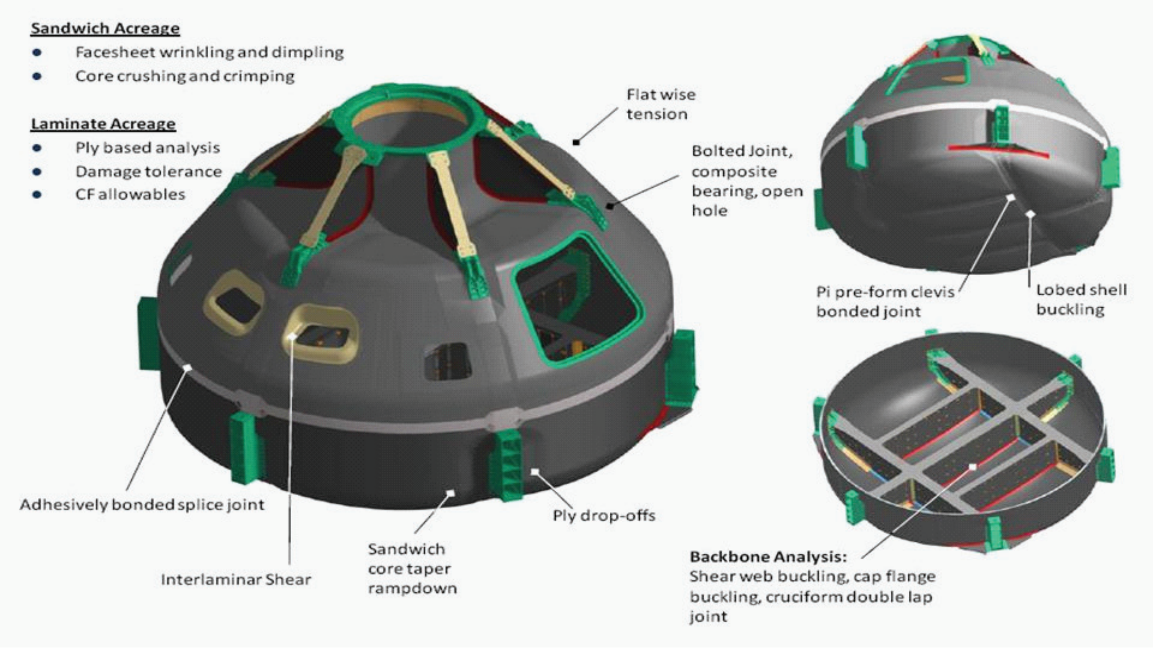

FIGURE 2-20 Structural features of composite crew module. SOURCE: Team Gains Experience as It Builds Innovative Composite Spacecraft. Available at http://www.nasa.gov/ offices/nesc/home/Feature_6_090908.html.

- Analysis for fabrication/manufacturing features, which included cutouts, sandwich ramp-downs, laminate ply drops, fabric ply overlap regions, and fiber angle alignment.

The CCM is constructed in two main parts: an upper pressure cell and a lower pressure shell. The two halves are joined outside the autoclave to enable the packaging of large or complex subsystems. Building block tests of critical design and technology areas were conducted to validate critical assumptions and design allowables. Full-scale fabrication of the upper and lower pressure shells began in 2008. Successful testing of CCM was carried out in July 2009. Project director Mike Kirsch estimates that the CCM is 10-15 percent lighter than its aluminum counterpart on the Orion crew vehicle.[56]

2.5.6 Modernization of the Kiowa Warrior OH-58D

The mission of the Kiowa Warrior, a single-engine, two-man helicopter, is “to support combat and contingency operations with a light, rapidly deployable helicopter capable of armed reconnaissance, security, target acquisition and designation, command and control, light attack, and defensive air combat mission.”[57]

Originally deployed in 1969 to Vietnam as the OH-58A, the Kiowa was based on a successful commercial helicopter, the Bell 206. The OH-58D (Figure 2-21), prototyped in 1983 and first flown in 1985, is currently the dominant version of the helicopter, having flown more than 400,000 hours in Iraq and almost 39,000 hours in

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[56] For more information, see M. Kirsch, 2009, “Broad Based Teams, Case Study #1—Composite Crew Module.” Presented in Project Management Challenge 2009, Daytona Beach, Fla., available at http://pmchallenge.gsfc.nasa.gov/docs/2009/presentations/Kirsch.Mike.pdf; or B.A. Bednarcyk, S.M. Arnold, C.S. Collier, and P.W. Yarrington. 2007. “Preliminary Structural Sizing and Alternative Material Trade Study of CEV Crew Module.” NASA TM-2007-214947; AIAA-2007-2175.

[57] For more information on the Kiowa Warrior, see http://www.fas.org/man/dod-101/sys/land/wsh2010/198.pdf. Last accessed October 19, 2011.

FIGURE 2-21 Bell OH-58D Kiowa military helicopter with full ammunition. SOURCE: Available at http://www4.army.mil/armyimages/armyimage.php?photo=3873.

Afghanistan (about 80 flight-hours per helicopter per month), accounting for more than half the total reconnaissance/attack hours.[58] The Army's current fleet is 340 OH-58Ds, and many others have been sold internationally.

The Kiowa Warrior was viewed as a temporary program, to be replaced by the RAH-66 Comanche—the Army's next-generation, lightweight, low-cost armed reconnaissance helicopter. The Comanche program faced numerous difficulties—it underwent six restructurings and a drawn-out schedule, with inconsistent funding from year to year. When it was canceled in 2004, one of its performance shortcomings was not meeting its lightweighting goals. A second proposed replacement for the Kiowa, the Bell ARH-70, was canceled in 2008.

The Kiowas were originally intended to be unarmed scouts, but with delays and then cancellation of the RAH-66 Comanche and the ARH-70 Arapaho, the OH-58D has become the Army's armed reconnaissance helicopter. As these helicopters have aged, maintenance has become more difficult, and the technology outdated. Funding intended for the next-generation helicopters will be used instead for modernization. In October 2010, the Army announced specifications for the Fox model—upgrades to the OH-58D Kiowa Warrior, which will be designated OH-58F.

OH-58D Upgrade: Improved Performance via Lightweighting

Lightweighting is a viable strategy within a vehicle modernization program.

Many of the planned upgrades are aimed at reducing weight. One of the top priorities is an engine that will increase the power-to-weight ratio, which is particularly important in mountainous areas such as Afghanistan. Rolls-Royce is working to increase the power of the Kiowa's current engine by 12 percent. At the same time, Bell is working with the Honeywell engine that was to be used on the Arapaho; it would add about 100 lb but provide 50 percent more power.[59]

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[58] M. Rusling, 2010, "With No Replacement in Sight, Army's Oldest Helos Keep Going," *National Defense,* April; and "Army New Kiowa Warrior FOX Model Increases Capability," *Defense Daily,* October 27.

[59] S. Trimble. 2010. "U.S. Army Announces New Fox Model for Kiowa Warrior." *Flightglobal,* October 26.

The Kiowa Warrior's machine guns will be replaced by Avenger's M3P machine guns, which use a simple mount that avoids the need for a gun cage assembly. The new system is 65 lb lighter than its predecessor, which Ron Bridges of Redstone Arsenal estimates will save $20,000 per pound over the life of the helicopter."[60] Lifeport Interiors Inc. has developed and tested lightweight floor armor; the installed kit weighs 8.6 lb and is capable of defeating 7.62 rounds.[61]

2.6 CONCLUSIONS

Aircraft—both military and commercial—have long used lightweighting because of its strong connection to performance. Lightweighting not only reduces fuel costs but also determines range. Composites are increasingly replacing aluminum in aircraft. The great barrier to further lightweighting in aircraft is that the development time for new composites exceeds the development time for aircraft. The committee reached the following conclusions about lightweighting aircraft and the need to accelerate the materials development cycle:

- Because the development of composite materials takes 10 years or more, materials must be under development long before aircraft definition takes place. New materials must always be in the pipeline and being brought to maturity to provide the capabilities foreseen in the strategic plans of the armed forces.
- The long timeline for materials development also points to the need for computational materials engineering to bring the synthesis of new resins and fabrication processes into the digital age. Advancements in computational chemistry may make it possible to design the molecular structure of the resin to meet structural and other requirements for a given application. Processing science will be an integral part of this methodology to ensure that section thicknesses and shapes can be fabricated from the designed resins.
- Currently available empirical analysis tools cannot replace the testing required to support composite applications for commercial aircraft. Better analytical methods are required and better definition of test variability is also required to allow testing for means and not for distributions.
- Part of the materials pipeline should be devoted to the development of multifunctional materials and structures, and the processes by which such structures can be manufactured. The more requirements can be met with multifunctional materials, the less design complexity is needed for structural integration of multiple systems. Some of the key multifunctional capabilities that need to be met with new materials include strength and electromechanical energy dissipation and shielding; dynamic or sonic vibration damping; greater tolerance of extreme temperatures; and resistance to damage from hail or foreign objects.
- Integrated computational materials engineering (ICME) is a promising strategy for improving the analytical models of the strength of composite materials and the models for predicting the variation in composite laminates given the mean strength capability. First-level models for predicting the behaviors of today's materials have been developed, and some elements of ICME, such as chemical modeling of resins, are already being used to develop the materials needed for tomorrow. However, much more is still needed to provide rapid, accurate, and reliable methods for predicting the performance of composite materials that would reduce the enormous amount of testing required to design aircraft today.
- Another promising strategy for accelerating the introduction of new materials for lightweighting is the DoD's advanced technology demonstration program, which needs to use a systems engineering approach that includes all known threats and all the requirements set for operational systems. The ATD demonstration data can then be used to reduce the amount of testing required to certify the operational system.
- Despite having pushed the lightweight boundaries for many years, the aerospace industry still has a long way to go before affordable lightweight structures can be easily designed, certified, and maintained.
- Taking advantage of Title III funding could provide some relief to develop and mature advanced materials (e.g., titanium metal matrix composites) when they are too expensive to buy in large quantities. Such relief would no longer be needed once material costs are reduced to affordable levels.

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[60] K. Hawkins. 2009. "Kiowa Warrior Gains Firepower." *Redstone [Arsenal] Rocket,* May 6. Available at http://www.army.mil/article/20656/.

[61] "Army New Kiowa Warrior FOX Model Increases Capability." *Defense Daily*, October 27, 2010.

3

Lightweighting Maritime Vehicles

3.1 CURRENT STATE OF LIGHTWEIGHTING IMPLEMENTATION AND METRICS

3.1.1 Drivers of Lightweighting

Lightweighting of maritime platforms is driven by the following objectives:

- Reduce fuel consumption;
- Improve speed, maneuverability, and transportability;
- Increase weapons payload.

These desired attributes are balanced against cost constraints and survivability. Smaller vessels are often built entirely with lightweight materials in order to achieve desired high-speed performance or transportability objectives. Larger ships tend to use lightweight materials for structures above the main deck. This has the effect of reducing ship weight and improving stability without diminishing overall hull girder stiffness.

3.1.2 Historical and Current Lightweighting

The U.S. Navy has had a mixed experience in introducing lightweighting into new maritime platforms. U.S. maritime vehicles have benefited from lightweighting materials such as:

- Composite construction (see examples in Sections 3.3.2 Deckhouses, 3.5.7 Mark V Special Operations Craft, 3.5.8 Advanced Enclosed Mast System, 3.5.9 Swedish *Visby* Class Carbon Fiber Warship),
- Use of aluminum in place of steel (see examples in Sections 3.5.2 Littoral Combat Ships and 3.5.6 Joint High-Speed Vessel), and
- High-strength steel (see examples in Sections 3.5.2 Littoral Combat Ships and 3.5.4 High-Strength Steel in Aircraft Carriers).

However, when survivability is more important than cost or speed, the projects have increased knowledge of new materials and manufacturing processes, but few of these advancements have yet been fielded. For example, see Sections 3.5.3 Marine Corps Expeditionary Fighting Vehicle and 3.5.4 High-Strength Steel in Aircraft Carriers.

TABLE 3-1 U.S. Navy Current and Future Fleet Composition

Ship Type	FY 2009	FY 2016	FY 2028	FY 2040
Aircraft carrier	11	11	11	11
Large surface combatant	88	90	85	76
Small surface combatant	55	32	46	55
Attack submarine	48	51	41	45
Guided missile submarine	4	4	–	–
Ballistic missile submarine	14	14	13	12
Amphibious warfare ship	31	33	36	30
Combat logistics force ship	30	30	26	28
Support ship	20	27	46	44

SOURCE: U.S. Director, Warfare Integration (OPNAV N8F), Report to Congress on Annual Long-Range Plan for Construction of Naval Navy Vessels for FY 2011, February, 2010.

Current and planned Department of Defense (DoD) maritime assets include a number of platforms that could be improved with lightweight structural materials.

All of the DoD services that interface with the sea have a fleet of maritime assets to support their mission responsibilities. The Navy is responsible for procuring larger ships for all of the services, and the Military Sealift Command operates support ships with civilian crews. In order to understand the potential for lightweighting future ships it is instructive to briefly look at the mission requirements and assets for each of the services individually.

Navy

In a February 2010 report to Congress, the Navy presented a snapshot (Table 3-1) of existing and planned ships in its inventory to best meet anticipated threats. To sustain the fleet targets shown in Table 3-1, new ship construction is projected to follow the plan shown in Figure 3-1.

The Navy is constantly struggling to define future ship requirements while taking into consideration evolving threat scenarios, construction cost growth, long design development times, and limited acquisition budgets. In this continuing process, the Navy has canceled some new platform programs using lightweighting and has increased others. See Sections 3.5.1 and 3.5.2.

Army

The Army has 119 watercraft of various classes in its fleet. A number of the Army's watercraft are barges and small boats to support harbor operations. The Army's watercraft assets are also designed to support joint logistics over the shore (JLOTS) operations with the Navy to deliver personnel, munitions, and wheeled/tracked vehicles to bare-beach environments.[1] The development of a Modular Causeway System and a fleet of joint high-speed vessels (JHSVs) purposely built for the Army will augment this capability. There are no immediate plans to replace the Army's fleet of logistic support vessels (LSVs) or landing craft, utility (LCUs).

Marine Corps

The U.S. Marine Corps relies on the Navy's amphibious ship fleet to maintain its readiness worldwide to land marines and their equipment for military and humanitarian relief operations. That force currently stands at 31 ships, although it is estimated that 38 are required in inventory to maintain 17 in a "forward deployed" condition.[2] The landing craft, air cushion (LCAC) currently shuttles marines and their equipment from larger amphibious ships stationed a safe distance offshore over unimproved beachheads. The larger ship-to-shore connector (SSC) is the

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[1] 2010 Army Modernization Strategy, April, 2010, available at www.G8.army.mil.

[2] U.S Marine Headquarters, Office of Public Affairs, Amphibious Shipbuilding, June 2010.

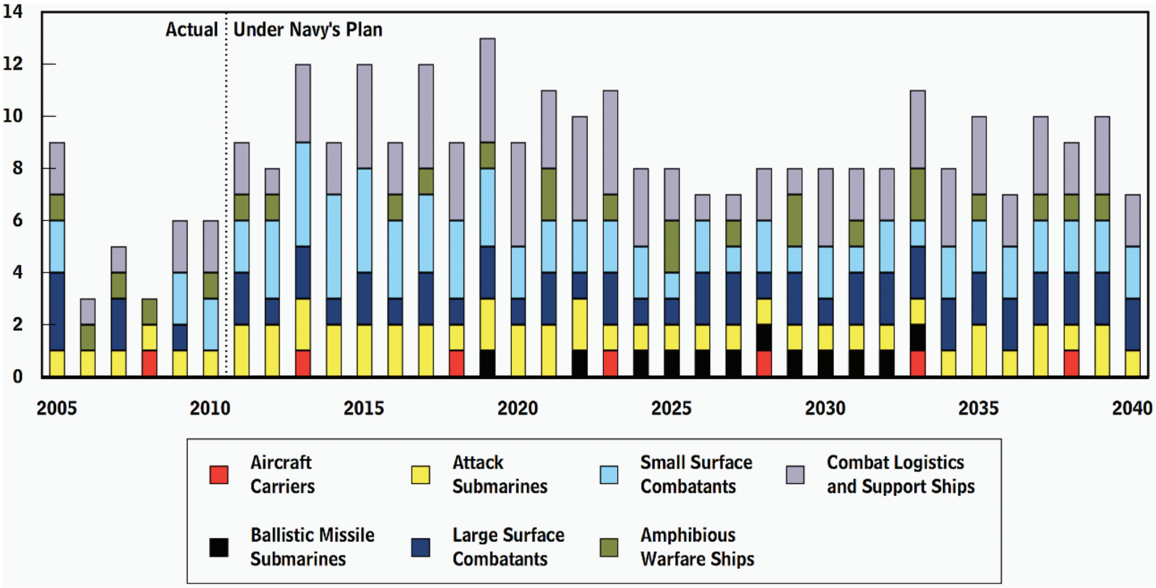

FIGURE 3-1 Projected U.S. Navy new-build requirements. SOURCE: Congressional Budget Office, "An Analysis of the Navy's Fiscal Year 2011 Shipbuilding Plan," May 2010.

planned replacement for the LCAC. The motivation for its design is to increase payload and improve reliability and maintainability.[3] By making extensive use of aluminum for lightweighting, the SSC will exceed the LCAC in speed, payload, and range.

The marines also have an inventory of much smaller assault and reconnaissance boats that must be transported to theaters of operation. An expeditionary fighting vehicle (EFV) that could be launched from a safe distance offshore and then operate over land was, in concept, a model for lightweighting: it was intended to be heavily armored yet able to move quickly at sea and on land. It was canceled in January 2011 when it was behind schedule and over budget. Its replacement is likely to have a lower expectation for speed at sea.[4] See Section 3.5.3.

3.1.3 Current State of Metrics

A very large empirical database has been accumulated based on building ships with steel. Maximizing the benefit of lightweight material will require long-term validation of design strategies and fabrication techniques for materials other than steel.

The lightweighting of U.S. DoD maritime platforms typically occurs at the design stage, because it is very difficult to retrofit large structural elements on complex ships. In particular, materials dramatically influence all aspects of a ship's life cycle, and so the selection of materials for lightweighting ships must come early in the design process. Material mechanical properties determine a ship's structural design, while manufacturing considerations greatly influence cost. Modular construction practices that maximize the size of lightweight structural elements fabricated before assembly can greatly reduce labor costs. As the DoD looks to get longer service life from its maritime platforms, the ability of material systems to withstand the ocean environment is paramount.

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[3] Capt. C. Mercer, "Ship to Shore Connector: A Turning Point in Naval Ship Design," September 9, 2010, available at www.navalengineers.org/flagship/.../ASNE_Luncheon_SSC_Turning%20Point%20in%20Naval%20Ship%20Design-9-8-10.ppt.

[4] Matthew Potter. 2011. "U.S. Marine Corps Begins EFV Replacement Process—Updated." *Defense Procurement News*. March 7. Available at http://www.defenseprocurementnews.com/2011/03/07/u-s-marine-corps-begins-efv-replacement-process/#ixzz1Md3Pu4fZ.

Material Properties

Material properties are typically determined at the coupon level in a laboratory environment. These data form the basis for developing "design allowable" mechanical property data. Novel materials require additional characterization, because naval designers have little or no empirical data to help formulate safety factors.[5] As a minimum, the following material properties need to be quantified at the "coupon" or "panel" level to develop novel materials for lightweighting:

- *Strength and stiffness*. Required data include tension, compression, shear, and Poisson's ratio values measured along three mutually orthogonal axes for anisotropic materials.
- *Dynamic properties*. Relevant dynamic material behavior includes impact, fatigue, and creep resistance.
- *Environmental effects*. Resistance to water absorption, corrosion, UV exposure, and fire are an important qualitative metric.

Design Criteria

The criteria used to design lightweight ship structures have a major influence on how well those materials are optimized. The design process begins with a detailed understanding of the loads that the ship will experience over its lifetime and how the structure will respond to those loads. A fairly good understanding of how mild steel ship structures perform in the ocean exists, but novel materials generally require larger design safety factors because of the more limited knowledge base on their performance.

Manufacturing Process

DoD ships are extraordinarily complicated engineered structures, built by joining plates into successively larger assemblies. A steel ship contains miles of weldments at the joints, making welding not only labor intensive but also critical to the ship's structural integrity. Even small defects in weldments can grow to large cracks that eventually cause failures.[6]

With steel shipbuilding, plates, I-beams, and structural "tees" arrive at the shipyard with known physical properties, as specified by the yard and confirmed by quality assurance personnel. Construction using composite materials poses additional manufacturing risks, because laminators create the "plates" themselves in the shipyard. Metrics for shipbuilding reflect cost tradeoffs between weldability of materials and the skilled labor needed for materials that are more challenging to weld.

In-Service Performance

Selection of lightweight ship structural materials must also take into consideration the operational profile of the ship and how materials are expected to perform. In-service variables include expected sea states, operating speeds, temperature, docking and handling, coatings, equipment attachment, insulation, and passive fire protection.

Life-Cycle Costs

Life-cycle costs to be considered include the cost of materials, fabrication costs, maintenance costs, cost to inspect and repair, alteration costs, and the cost to recycle or dispose of the ship at the end of its useful life.[7] Among competing systems, the one with the lowest procurement cost is unlikely to have the lowest life-cycle cost—steps taken to reduce procurement costs typically reflect tradeoffs that push costs to maintenance, repair, or other later stage in the life cycle. Various models have been developed to predict life-cycle costs, but it is virtually impossible

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[5] See the discussion in "Uncertainty, Risk, and Design Factors" in Chapter 1 of this report.

[6] W. Babcock and E. Czyryca. 2003. "The Role of Materials in Ship Design and Operation." *AMPTIAC Quarterly*, Vol. 7, No. 3, pp. 31-36.

[7] NAVSEA. 2004. "Draft Material Selection Requirements." T9074-AX-GIB-010/1000. March.

to predict the operational threats and damage mechanisms that the system will face 20 years in the future. Thus, present design decisions generally do not reflect life-cycle costs.

3.2 BARRIERS AND KEYS TO SUCCESS FOR USE OF SELECTED MATERIALS

Advanced lightweight structural materials that show promise for application to DoD maritime platforms are diverse, each with its own technical challenges. Overcoming these challenges will require advances in material availability, design code maturity, qualification, manufacturing issues, and in-service performance. Because the committee views aluminum, composites, and high-strength steel as the most likely materials to be used for the primary structure of ship hulls in the near to mid-term, the following sections review barriers and keys to success for each material with respect to marine vessels.

3.2.1 Aluminum

Aluminum has been used as a ship construction material at least as far back as 1895, when the America's Cup yacht *Defender* was built with aluminum skins over steel frames. Some early aluminum boats lasted only a few weeks in seawater, which isn't surprising considering that copper or nickel was added to these early alloys and steel rivets were used, producing rapid galvanic corrosion.[8]

Bret Conner of Alcoa Defense's Sea Systems reports that all surface combatants from 1947 until the DDG-51 had aluminum in their deckhouses, at which time the Navy switched back to steel due to cracking problems. Dr. Conner stresses the following to avoid past problems with aluminum marine construction:[9]

- Prevent fatigue cracking by analyzing stresses, especially at details, and performing a spectral fatigue analysis;
- Prevent stress corrosion cracking by using marine plate with greater than 3 percent magnesium certified to ASTM B928 (if service temperatures exceed 65°C or 150°F, choose an alloy with less than 3 percent magnesium such as 5454); and
- Avoid galvanic corrosion by isolating aluminum from steel.

In a presentation to the committee, Robert Sielski outlined the following research needs required to advance aluminum ship construction: material property and behavior; structural design; structural details; welding and fabrication; joining aluminum to steel; residual stresses and distortion; fatigue design and analysis; fire protection; vibration; performance metrics, reliability, and risk assessment; maintenance and repair; structural health monitoring; and emerging technologies.[10,11] The largest identified knowledge gap is in the area of fatigue properties and fracture toughness, particularly dynamic fracture toughness.[12] As shown in Figure 3-2, technological advances that reduce fatigue crack growth are needed to promote greater use of aluminum hulls for lightweighting.

3.2.2 Composites

Composite materials have the greatest potential to lightweight DoD maritime platforms, especially smaller, high-speed craft. However, they also present the greatest challenges to more widespread use. Every aspect of a

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[8] Ship Structure Committee. 2007. "Aluminum Structure Design and Fabrication Guide." SSC-452. NTIS#PB2007. Available at http://www.shipstructure.org/pdf/452.pdf.

[9] Alcoa Defense, "Advantages of Aluminum in Marine Applications Webinar," April 2010. Available at http://www.alcoa.com/global/en/news/webinar/al_shipbuilding/alcoa_defense_and_abs_webinar.pdf.

[10] R.A. Sielski, Consulting Naval Architect—Structures (retired, Naval Sea Systems Command), "Lightweight Aluminum Structure for Ships and Craft," presentation to the committee, September 20.

[11] R.A. Sielski. 2007. "Research Needs in Aluminum Structure." 10th International Symposium on Practical Design of Ships and Other Floating Structures. September.

[12] Ibid.

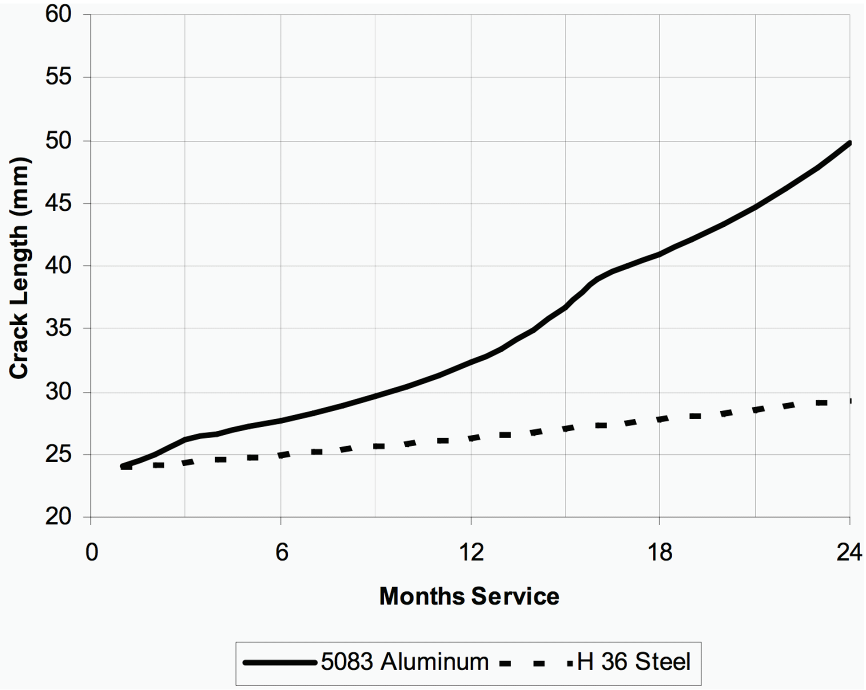

FIGURE 3-2 Predicted crack growth for a 4.39-m 32-knot craft. SOURCE: R.A. Sielski, "Aluminum Structure Design and Fabrication Guide," Ship Structure Committee Report SSC 452, May 2007.

composite structure is created by shipbuilders from basic materials, which results in a great deal of variability in the materials' mechanical properties. The myriad combinations of constituent elements in composite materials make it difficult to establish a comprehensive set of material design properties for all but the most common laminates.

Material Availability

Large ships use a massive quantity of structural material and can affect market availability of precursor and finished materials. This is especially true when novel, high-performance materials are used, such as the T700 carbon fiber for the DDG 1000 deckhouse. To meet their missions, military projects require materials that have higher levels of quality assurance than recreational applications do, which increase the cost to the government. However, greater demand for a product such as intermediate-modulus carbon fiber can also increase domestic production and create long-term price stability. Indeed, the DoD requirement for domestically sourced structural materials has provided justification for suppliers to develop production facilities in the United States.

Composite materials have stringent storage and handling requirements that can also influence the availability of a product at the shipyard. Resins have a limited shelf life, while reinforcements and cores must be kept dry.

Qualification Issues

The Navy has a number of technical warrant holders that must certify the safety of all material systems used to build ships. This arrangement accounts for the excellent safety record enjoyed by the fleet but discourages the use of new composite materials in lightweighting.

Manufacturing Variability

With the widespread use of vacuum-assisted resin transfer molding (VARTM), the variability of composite construction has certainly been reduced. Indeed, for most of the case studies described in this report, large panels were fabricated on flat laminating tables under very controlled conditions. The greater challenge is to join these panels and outfit the ship. Steel shipbuilding has long recognized the need to train and certify welders. Composite shipyards (i.e., those that build ships with composite hulls) are now instituting training and qualification programs, albeit generally with curricula proprietary to each shipyard. Shipbuilding with composite materials requires detailed process descriptions and a rigorous quality assurance program.

Inspection and Repair

With metallic structures, failures generally occur at welds and are visually apparent. In contrast, sandwich composite structures have failure modes that are not often apparent upon visual inspection. Delamination can occur within the laminate skins or between the skins and the core. The core can fail due to excessive stress or water ingress. Ultrasonic inspection techniques developed for the aerospace industry are difficult to scale up for the large surface areas and limited access of ships.

Repair techniques for large composite structures are very well developed and take advantage of the versatility associated with composite construction. Entire bow sections of commercial fishing vessels have been repaired after collisions by molding large, complex sections and joining them to the undamaged hull portions. Adequate strength properties can be achieved if sufficient scarf ratios are used.

Recycling

Because composites are not subject to corrosion, they will last longer than metal in a marine environment. Therefore, entire boats can be "recycled" for extended service through re-outfitting. When the structure needs to be permanently disposed of, however, recycling of composite shipbuilding materials remains a challenge. The current options are grinding for future use as filler material or incineration for power generation. Development of new recycling technologies is expected as wind turbine blades that were designed to last for 20 years reach the ends of their life spans.

3.2.3 High-Strength Steel

High-strength steel plate constitutes increasing portions of the hull structure in modern warships, surface combatants, and submarines for weight reduction, better stability, increased payload, increased mobility, and survivability. Naval shipbuilding accounts for nearly 50 percent of the total DoD requirement for alloy and armor steel plate. The U.S. Navy qualified HSLA-65 steel in 2005 by focusing on welded structure compressive properties, local stability of stiffener elements, plate buckling, lateral deformation of plates, fatigue strength, and grillage strength.[13] HSLA-115 shows promise where material strength is paramount. The 16th International Ship and Offshore Structures Congress reports:

> HSLA steels (low carbon, copper precipitation strengthened ones, whose strength and toughness are equivalent to those of HY steels, and that can be easily welded without preheating) can ensure a higher resistance when subject to sudden impact loads, like underwater explosions. On the other hand, there is no practical advantage in using such steels when cyclic loads are dominant as *fatigue behavior is not dependent on the steel used but on the geometry of structural details and the quality of production*. In this case the use of HSLA may lead to significant problems due

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[13] E.J. Czyryca, D.P. Kihl, and R. DeNale. 2003. "NSWCCD, Meeting the Challenge of Higher Strength, Lighter Warships," *AMPTIAC,* Vol. 7, No. 3, pp. 63-70. Available at http://msp.berkeley.edu/jomms/2007/2-10/jomms-v2-n10-p06-p.pdf.

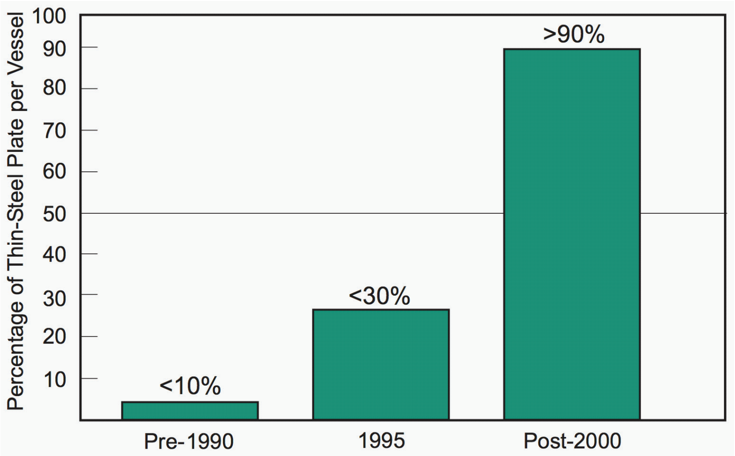

FIGURE 3-3 Thin steel plate use on Northrop Grumman Ship Systems ships. SOURCE: P. Huang, T.D. Dong, L.A. DeCan, and D.D. Harwig. 2003. "Residual Stresses and Distortions in Lightweight Ship Panel Structures." Northrop Grumman Ship Systems, *Technology Review Journal*, Vol. 11, No. 1.

> to the much more accurate production procedures required (welded joints, if not correctly carried out, may become fragile and more notch sensitive—thus more likely to experience fatigue cracks).[14]

At Northrop Grumman Ship Systems (NGSS), for example, the production ratio of thin-steel (10 mm or less) to thick-plate structures has risen to more than 90 percent. New designs are calling for the application of even thinner (e.g., 5 mm) high-strength steel grades to further reduce weight and improve performance.[15] Figure 3-3 shows the rapid increase in thin steel plate utilization for naval shipbuilding.

The increased use of lightweight steel panel structures has created challenges for shipbuilders to produce distortion-free ships. "Residual stresses and distortions induced by steel mill processing, as well as material-handling and manufacturing processes, such as cutting, tacking, and welding, cause progressive problems in downstream manufacturing/fabrication operations."[16] The referenced report suggests handling, cutting, and welding procedures designed to minimize local buckling, which is the dominant distortion phenomenon at NGSS.

3.2.4 Other Materials

A sandwich plate system (SPS) has been developed that uses steel skin panels and an injected elastomer core to create a sandwich structure that has very good out-of-plane mechanical properties. The technology is attractive for ship lightweighting, as the panel skins are composed of traditional shipbuilding steel, which is durable and easy to weld to the rest of the ship structure. One concern for naval applications would be the reduction in shear strength of the core material at elevated temperature.[17]

According to a 2003 assessment,[18] the SPS technology has been shown to have equivalent or better fire safety

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[14] 16th International Ship and Offshore Structures Congress. Southampton, United Kingdom, August 20-25, 2006. P. 244. Available at http://www.issc.ac/img/r13.pdf.

[15] T.D. Huang, D.D. Harwig, P. Dong, and L.A. DeCan. 2005. "Engineering and Ship Production Technology for Lightweight Structures." *Technology Review Journal*, Vol. 13, No.1, Spring/Summer, pp. 1-26.

[16] T.D. Huang, P. Dong, L.A. DeCan and D.D. Harwig. 2003. "Residual Stresses and Distortions in Lightweight Ship Panel Structures, Northrop Grumman Ship Systems." *Technology Review Journal*, Vol. 11, No. 1.

[17] Lloyds Register. 2006. "Provisional Rules for the Application of Sandwich Panel Construction to Ship Structure." April. Available at http://www.ie-sps.com/downloads/419.pdf.

[18] M.A. Brooking and S.J. Kennedy. 2003. "The Performance, Safety and Production Benefits of SPS Structures for Double Hull Tankers." Intelligent Engineering, Ltd. August.

to traditional steel structure when both are protected by structural fire protection. Of greater concern would be areas that do not have structural fire protection, such as the top side of decks and the exterior side of bulkheads. The same assessment also states:

> If an SPS panel is directly exposed to fire for an extended period then the elastomer core acts as sacrificial layer on the fire side (ablation) and gases from the elastomer surface vent into the fire side through temperature controlled pressure release valves.[19]

Without an integral core, the SPS cannot function as a sandwich structure and panel-buckling resistance would be greatly compromised. The Navy would certainly require fire testing to the hydrocarbon fire test criteria, which use roughly twice the fire insult used to qualify SPS for commercial ship applications.

3.3 LIGHTWEIGHTING OPPORTUNITIES FOR MARITIME VEHICLES

Ship designers have been striving to lightweight their craft for as long as people have ventured offshore. A hull moving through the ocean encounters a great deal of resistance from the water, so boats with less displacement encounter less resistance and can move faster. Reducing weight high up increases a vessel's stability and survivability. The potential for lightweighting modern warships is quite large because of the ability to create multifunctional structures.

Ship structure needs to keep the ship afloat, resist wave loads, survive combat conditions, insulate the interior, and resist fires. Modern warships are increasingly incorporating apertures for integrated sensors.[20] With advanced computer-aided design and simulation tools, load conditions and structural response can be predicted more accurately, allowing for further weight optimization. Naval architecture is a classic "systems engineering" discipline that uses an iterative optimization process.

3.3.1 Primary Hull Structure

The potential for lightweighting the primary hull structure of very large ships is limited by stiffness and fatigue considerations. To date, the largest aluminum ship is 127 m and the largest composite ship is 75 m. These milestones will likely be surpassed as more at-sea experience with lightweight vehicles accumulates. However, even ships of 75 m or less are very useful for many DoD maritime missions that require speed and stealth. An example—the joint high-speed vehicle—is described in Section 3.5.6.

Lightweight materials are especially attractive for novel hull forms, such as multihulls, surface effect ships (SES) and hovercrafts. These ships require lightweight hulls yet have more surface area than their monohull counterparts. Ships that achieve high-speed performance by planning or other means of dynamic support must be lightweight in order to perform as designed.

Several technologies will help to lightweight primary hull structures. Ubiquitous structural health monitoring using low-cost, wireless sensors or sensors that are integral with hull plating will permit optimization of scantlings. Design criteria for structural details are currently based on previously observed damage. With real-time strain data, the ship designer will be better equipped to optimize the structure. These data are especially needed in the wave slam areas of high-speed ships.

Investigating multifunctionality opportunities can also help to optimize primary hull structure. Parasitic weight is added to hull structures in order to achieve thermal insulation, structural fire protection, and corrosion and biofouling resistance. Developing material systems that incorporate all these functions will not only lightweight the ship but also decrease required manufacturing and maintenance labor.

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[19] Ibid.

[20] Such as various types of radar systems. See, for example, "Use of Composite Materials for Weight Reduction in Navy Applications," presentation to the committee by G. Camponeschi, Naval Surface Warfare Center, July 21, 2010.

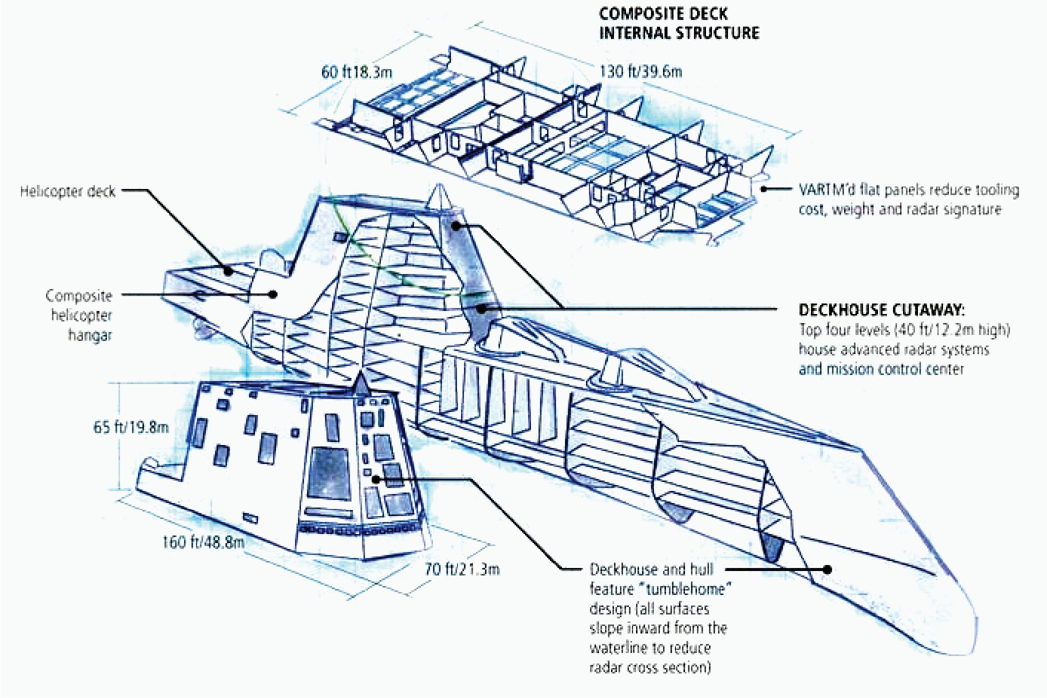

FIGURE 3-4 DDG Zumwalt destroyer composite deckhouse superstructure. SOURCE: Illustration by Karl Reque, from M. LeGault, 2010, "DDG-1000 Zumwalt: Stealth Warship," *Composites Technology,* February.

3.3.2 Deckhouses

Deckhouses are the first place ship designers look for lightweighting opportunities. This is because deckhouse structure is not expected to contribute to hull girder strength and stiffness, thus making it possible to use a lower modulus material.

For example, the 160 ft long by 70 ft wide by 65 ft high deckhouse of the Navy's newest destroyer will be a composite structure built using carbon fiber, vinylester resin, and a balsa core. Use of composites will allow the Navy to reduce topside weight, platform signature and to integrate apertures into the structure.[21] According to Barry Heaps, Northrop Grumman Shipbuilding program manager/director DDG-1000 Deckhouse, carbon fiber was used instead of E-glass because "the structural load requirements for the . . . deckhouse are significantly higher than those for LPD masts."[22] Figure 3-4 illustrates the composite deckhouse.

3.3.3 Secondary Structure

Large ships have thousands of square meters of secondary structure that could be lightweighted if adequate structural and fire resistance characteristics can be achieved. The LASS project (Section 3.5.5) addressed fire performance issues with cost-effective solutions. The study showed that sandwich composite panels have excellent out-of-plane mechanical properties required of internal decks and bulkheads.

Corrugated stainless steel panels (LASCOR) have also been proposed for secondary structure on naval ships. ATI reports that ATI 2003® lean duplex stainless is being used to manufacture LASCOR panels for personnel safety

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[21] E.T. Camponeschi. 2010. "Carbon Fiber Composites in DDG 1000." Presentations to the committee in October 2009 and on July 21, 2010.

[22] M.R. LeGault. 2010. "DDG-1000 Zumwalt: Stealth Warship." *Composites Technology.* February. Available at http://www.compositesworld.com/articles/ddg-1000-zumwalt-stealth-warship.

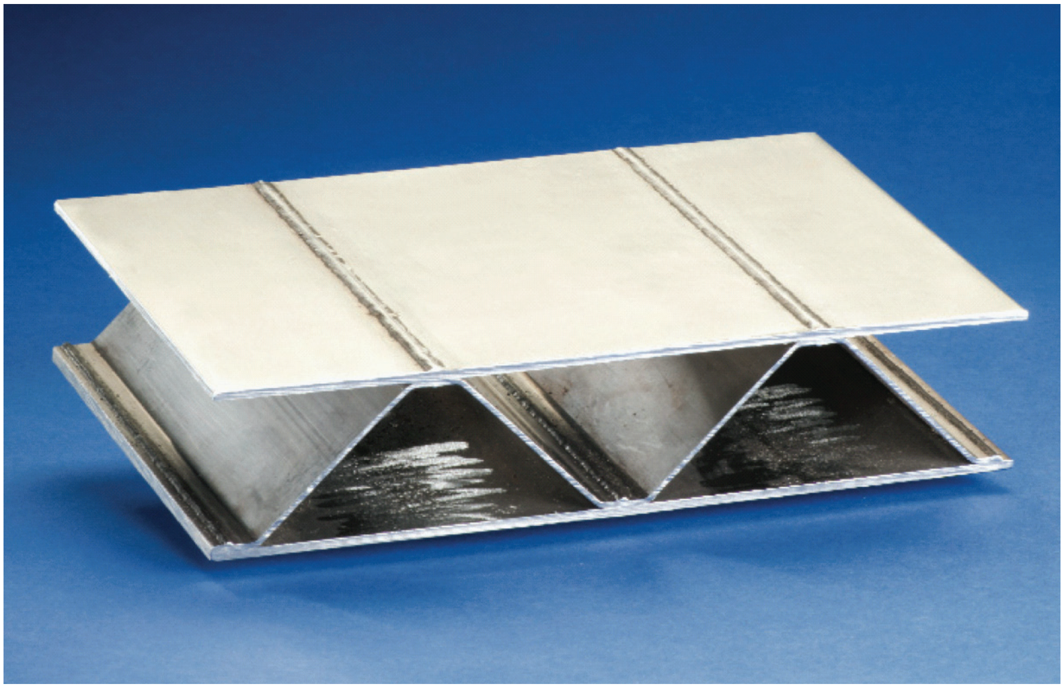

FIGURE 3-5 LASCOR (LASer-welded corrugated CORe) panel. SOURCE: S. O'Connor. 2010. "U.S. Navy Uses Proprietary ATI Alloy for New Destroyer Ships." *ATI Defense*. March.

barriers on the DDG 1000 destroyer ship. ATS successfully manufactured numerous large (78 × 240-inch) LASCOR panels for a number of structural tests.[23] Figure 3-5 shows the structural configuration of LASCOR panels.

3.3.4 Outfitting

Reducing the weight of DoD maritime platforms by lightweighting outfitting elements is generally beyond the scope of this report but it is instructive to look at opportunities as part of the overall ship design process. Composites have been used for piping, pump housings, ventilation ducts, ladders, gratings, electrical enclosures, shafts, and foundations. The Navy has also considered titanium piping and heat exchangers.

3.3.5 Unmanned Maritime Vehicles

The committee has not assessed the potential for lightweighting in unmanned surface vehicles (USVs) or unmanned underwater vehicles (UUVs). A review of the history of USV development notes,

> As global positioning systems have become more compact, effective, and affordable, unmanned surface vehicles have become more capable. Despite this proliferation of proven prototypes there are few USVs on the market or in use, especially compared to their unmanned undersea vehicle (UUV) cousins. This paper concludes with a discussion of some emerging new trends in USVs and the challenges to wider adoption of the technology.[24]

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[23] S. O'Connor. 2010. "U.S. Navy Uses Proprietary ATI Alloy for New Destroyer Ships." *ATI Defense*. March. Available at http://www.atimetals.com/defense/docs/ATI2003Destroyer.pdf. Last accessed November 18, 2011.

[24] Justin Manley. 2008. "Unmanned Surface Vehicles, 15 Years of Development." 978-1-4244-2620-1/08. MTS/IEEE OCEANS 2008 Conference. Quebec City. Available at http://www.oceanicengineering.org/history/080515-175.pdf. Last accessed October 19, 2011.

3.4 LONG-TERM CONCERNS IN LIGHTWEIGHTING MARITIME VEHICLES

Although high-performance racing boats are often the genesis of lightweighting concepts, the DoD requires platforms that can be supported over an expected 40-year life. Initial decisions about material selection, fabrication, and documentation can greatly influence the long-term value of a maritime asset.

3.4.1 Design Methodology

One of the most cost-efficient ways to lightweight ships is to more accurately predict local stresses and failure modes, as described in Section 3.2.1. Ships are by necessity conservative structures due to uncertainty about the ocean environment and how the ship will interact with it. By definition, waves are repetitive forces, so fatigue performance is of paramount importance. For composite materials, crack propagation is not an area of concern but delamination and secondary bond areas (joints) are. For metallic structures, weld areas require additional design attention. Long-term optimization of ship design requires validation of structural performance. Wave damage to a Mark V Special Operations Craft, shown in Figure 3-6, highlights the pressing need for a better understanding of both effective craft design and material capabilities and limitations. The Navy design community is acutely aware of the need for new models that account for corrosion; material degradation (sensitization, fatigue cracking); and deformation for life prediction and life-cycle management of platform structures.[25]

3.4.2 Material Availability

Regardless of the materials used for large maritime platforms, the massive quantity of structural material required can affect market availability of precursor and finished materials. This is especially true of novel, high-performance materials, such as the T700 carbon fiber for the DDG 1000 deckhouse. The following paragraphs address the material availability issues for composites, aluminum, and steel.

Composite structures require a number of individual materials, each of which is subject to its own supply challenges. The price of resin systems is directly proportional to the price of oil. Market demand from other industries also influences resin availability and cost. High-performance fibers, such as carbon, are produced in quantities and priced to meet the demands of the aerospace market and will remain a challenge for shipbuilders to utilize on a large scale. Specialized core material is also produced in limited quantities.

Aluminum ship construction costs are being driven down by the greater use of specialty extrusions, such as stiffened panels and weld joint products shown in Figure 3-7. The Navy Metalworking Center reports that the Lockheed Martin Team Littoral Combat Ship design makes extensive use of stiffened aluminum panels for construction of the ship's superstructure. These panels are built up from extruded aluminum shapes using friction stir welding (FSW) as the joining method.[26] In order to support ships built with these specialty products, their long-term availability must be assured.

The Navy's aircraft carrier program certainly has benefited by incorporating HSLA-115 in the design of the flight deck to improve stability. However, the specialized alloy is produced by only one supplier, which eliminates the possibility of any price competition.

3.4.3 Domestic Manufacturing Capability

Navy program managers are acutely aware of the sources of raw materials that they use and the stability of those regions. At a recent U.S. Office of Naval Research (ONR) energy conference it was noted that while imported oil may originate from unstable global regions, the lithium required for a battery-based transportation system is also not a domestic resource; most is mined in Bolivia. While titanium is attractive for maritime construction due to its light weight, high strength, and corrosion resistance, Russia is currently the primary source for most of this material.

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[25] P.E. Hess, 2008. "Structural Reliability Program." ONR Program Code 33. August.

[26] M.T. Smitherman and K.J. Colligan. 2008. "Low-Cost Friction Stir Welding of Aluminum for Littoral Combat Ship Applications." Navy Metalworking Center. August.

FIGURE 3-6 Wave damage to Mark V special operations craft. SOURCE: J. Grimsley and E.G. Hatchell. 2008. “Computational Tools for Combatant Craft.” NSWCCD, *SeaFrame,* Vol. 4, Issue 2.

The United States has a strong domestic capability to build lightweight boats, driven primarily by the demand for high-quality yachts and commercial crew boats.[27] Some manufacturers have demonstrated the ability to produce military prototypes for evaluation, but these rarely transform into production efforts due to government contracting requirements. Indeed the initial Littoral Combat Ship incurred cost overruns by both vendors due to failures to effectively use earned value management procedures required of major defense contractors.[28] Warships typically have more significant outfitting requirements than commercial vessels of the same tonnage, which increases cost and management complexity.

In a 2006 study commissioned by the ONR, it was found that mid-tier shipyards in the United States (i.e., those able to build up to a 400-ft medium-size combatant), “have limited knowledge of naval vessels.”[29] Mid-tier shipyards in the United States were rated lower, on average, than international mid-tier shipyards and U.S. first-tier shipyards on every criterion (pre-erection activities, ship construction and outfitting, and five others).[30] As a consequence of this situation, the Navy has looked overseas for this expertise—Scandinavia for composites, Australia for aluminum, and Italy for high-strength steel. Technology transfer programs are then used to establish U.S. partners, which disrupts the Navy’s traditional design and oversight relationships with established shipyards.

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[27] According to the National Marine Manufacturers Association’s 2010 Recreational Boating Statistical Abstract, “Recreational boating remains an important contributor to the U.S. economy, generating $30.4 billion in sales and services in 2010. . . .”

[28] C.J. Castelli. 2008. “Audit Exposes Failed Management of Troubled Littoral Warship.” *Inside the Navy.* February 4.

[29] First Marine International Ltd. 2006. “Capabilities Study of Mid-Tier U.S. Shipyard.” November. Available at http://www.cnst.us/Projects/capabilities_assessment.html.

[30] First Marine International Ltd. 2007. “Findings for the Global Shipbuilding Industrial Base Benchmarking Study, Part 2: Mid-Tier Shipyards, Final Redacted Report.” February 6.

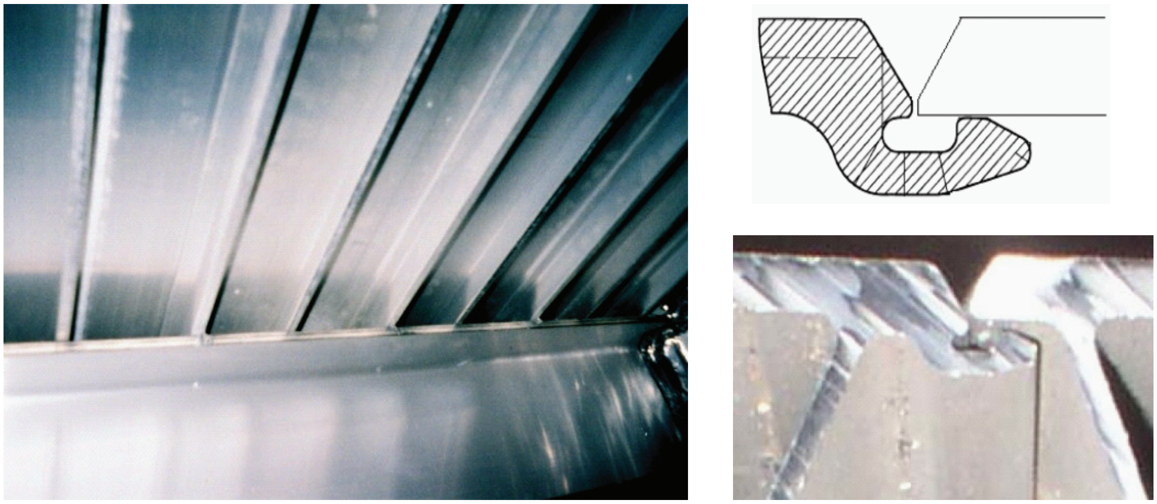

FIGURE 3-7 Aluminum stiffened panels (left) and weld joint (right) specialty extrusions. SOURCE: Brett Conner. 2010. "Advantages of Aluminum in Marine Construction." Segment Leader, Sea Systems, Alcoa Defense, Alcoa.

3.4.4 Structure Inspection and Repair

For maritime vehicles in particular, survivability refers not just to combat but perhaps more so to the effects of the environment (e.g., weather, waves, salt damage). The ultimate survivability of a ship rests on the ability to observe and repair damage before it becomes catastrophic. Benign failure modes, such as stiffener versus hull plating failure, form the basis for long-term structural integrity. However, minor failures must be observed and repaired. Many high-speed ship designs rely on complex hull structures that are not readily available for structural inspection, such as catamaran and surface effect ship hulls. Visual inspection is further hampered by thermal insulation or structural fire protection that covers hull plating and internal framing. Lightweighting strategies must include non-destructive evaluation (NDE) methodologies tailored to materials and structural systems employed. Material-specific repair procedures must also be prepared and validated.

3.4.5 Environmental Impact

The long-term environmental impact of a selected lightweight ship construction material includes overall life expectancy, corrosion resistance (need for preservation coatings), ease of recycling and the effects of catastrophic failure (sinking). Aluminum has a good track record for recycling; according to the Aluminum Association, 70 percent of the aluminum ever made is still in use today.[31] There is a vibrant industry for recycling steel from large ships after their useful life has expired, albeit in countries where labor costs are very low. Composite structures are more challenging to recycle. The material can be ground up for use as filler but in order to reuse the materials in a more virgin form the resin and reinforcement must be separated, which is an energy-intensive operation at this point.

3.5 EXAMPLES OF LIGHTWEIGHTING IN MARITIME VEHICLES

This section describes the role of lightweighting in a range of maritime vehicles—from U.S. and international maritime programs, and including a variety of vehicles, technologies, and maturity.

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[31] The Aluminum Association. 2008. "Aluminum Industry Takes Aim at Climate Change, More Efficient Technologies, Processes Point Way to Reducing Greenhouse Gas Emission." Available at http://www.aluminum.org/AM/Template.cfm?Section=Home&template=/CM/HTMLDisplay.cfm&ContentID=23520.

3.5.1 New Composites Developed for Advanced Destroyers[32]

The *Arleigh Burke* class destroyer is a multimission warship with offensive and defensive capabilities. DDG 51 *Arleigh Burke* was ordered in 1985, commissioned on July 4, 1991, and tested at sea throughout 1992. Since then, 21 destroyers using the original (Flight I) design have been commissioned, followed by 7 of the Flight II variant, and more than 25 of the Flight IIA variant, which was first commissioned in August 2000.

The destroyers became heavier with each increase in capability. The Flight IIA design added mine-avoidance capability, a pair of helicopter hangars, blast-hardened bulkheads, distributed electrical systems, and advanced networked systems. It achieves 30 knots or more in open seas and displaces 9,648.4 metric tons at full load.

DDG: Technological Progress but Canceled Program

The extensive testing required to certify new materials accounts for the excellent safety record enjoyed by the fleet but provides a challenge for lightweighting. Although the DDG 1000 program was limited to three ships, the composite materials developed, tested, and certified for the DDG 1000 deckhouse are available for future applications.

The next generation of advanced destroyers, initially intended to replace the DDG 51 platform by 2012, is the DDG 1000 (*Zumwalt* class). The DDG 1000 uses modern technology and takes advantage of lightweighting by, for example, having a composite DDG 1000 Deckhouse with integrated apertures and low signature profile. Two *Zumwalt*-class destroyers, of an anticipated 8-12, are under construction. In 2008, however, the decision was made to end the DDG 1000 program after three ships, and to modernize the DDG 51 fleet. According to Navy spokesman Lt. Clay Doss:

> We need traction and stability in our combatant lines to reach 313 ships, and we should not raid the combatant line to fund other shipbuilding priorities. . . . Even if we did not receive funding for the DDG 1000 class beyond the first two ships, the technology embedded in DDG 1000 will advance the Navy's future surface combatants.[33]

The DDG 1000, with its advanced functional capabilities, costs more per ship than its predecessor; however, it has contributed to the use of new composite materials in shipbuilding. According to Northrop Grumman:

> During the DDG 1000 engineering development phase, NGSB [Northrop Grumman Ship Building] produced more than 6,000 carbon fiber/vinyl-ester test articles that were successfully tested and validated for ship designs in radar cross section, co-site, material properties, joints, fire, corrosion, shielding effectiveness, fragmentation and blast.[34]

This level of testing is typical for what the U.S. Navy considers to be a "new" shipbuilding material. The Navy has a number of Technical Warrant Holders that must certify the safety of all material systems used to build ships. Thus, new materials are introduced via a cautious and time-consuming process, which accounts for the Navy's excellent safety record but is a deterrent to introducing new materials for lightweighting.

3.5.2 Two Designs—Aluminum and High-Strength Steel—for Littoral Combat Ships[35]

The Navy started the Littoral Combat Ship (LCS) program in 2002, as a small, fast, relatively inexpensive combat ship. Interchangeable mission modules would deploy manned and unmanned vehicles and sensors in support of mine, undersea and surface warfare missions. Other intended missions include peacetime engagement, maritime intercept operations, and homeland defense.

Light weight is essential to the performance of the LCS. It displaces about 3,000 tons (about the size of a light

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[32] This section draws on factual descriptions drawn from http://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=900&ct=4. Last accessed June 10, 2011.

[33] Quoted in C. Cavas, 2008, "DDG 1000 Program Will End at Two Ships," *Defense News,* July 22.

[34] C.P. Cavas. 2008. "DDG 1000 Deckhouse on Track." *Defense News.* September.

[35] This section draws on factual descriptions from http://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=1650&ct=4, accessed June 10, 2011; and R. O'Rourke, 2011, "Navy Littoral Combat Ship (LCS) Program: Background, Oversight Issues, and Options for Congress," RL33741, Congressional Research Service, April 29.

frigate or a Coast Guard cutter), allowing it to operate in coastal waters that are inaccessible to Navy cruisers and destroyers. It has a maximum speed of more than 40 knots, compared with just over 30 knots for the Navy's larger surface combatants. And it has a core crew of 40, plus 35 additional sailors to operate the mission packages, for a total of 75, compared with more than 200 sailors for a Navy frigate.[36]

The first two LCSs were delivered to the Navy by Lockheed Martin and General Dynamics in 2008 and 2009. As the costs escalated, the Navy terminated its cost-plus contacts with Lockheed Martin and General Dynamics in 2007. Fixed-price contracts for the next two LCSs were awarded to Austal USA/General Dynamics and Lockheed Martin in 2009, with the intention of choosing one of the teams to produce 10 additional ships. Figure 3-8 shows the all-aluminum trimaran built by the Austal USA team and the high-strength steel hull/aluminum deckhouse monohull from the Lockheed Martin team.

When both bids came in under the cost cap per ship, the Navy sought and in December 2010 received congressional approval to purchase 10 ships from each team.[37] LCS 3 and LCS 4 are now under construction and four more LCS are under contract. If the Navy's follows its 30-year shipbuilding plan for 55 sea-frames and 64 mission packages, the LCS would be one-sixth of the Navy's total fleet. Because of the likelihood of cost-effective upgrades to replace mission modules, the platform—which is not easily upgraded—assumes greater prominence as a determinant of life-cycle costs and vessel retirement.[38]

LCS: Different Materials, Same Missions

The lightweight construction needed to achieve the littoral combat ship's speed, maneuverability, and shallow draft did not depend on a single design and material. The aluminum and high-strength steel versions both met the Navy's specifications. It is too early to compare their long-term performance.

3.5.3 Lightweighting the Marine Corps Expeditionary Fighting Vehicle While Maintaining Survivability

Figure 3-9 shows the expeditionary fighting vehicle (EFV) that was being developed by the Marine Corps as a successor to the Marine Corps' existing amphibious assault vehicle (AAV), Amtrac (from "Amphibious Tractor"). It was intended to transport 17 troops from ships offshore to their inland destinations at higher speeds and from farther distances than the legacy AAV. The prototype EFV has a ballistic-grade aluminum hull to facilitate speeds of up to 25 knots in open water.

The U.S. Government Accountability Office (GAO) reported that "the EFV program has worked to provide improved protection against improvised explosive devices (IEDs) and other threats, but risks remain."[39] It noted that the current design is projected to have a level of protection generally comparable to the AAV with its armor appliqué. New aluminum alloys and welding processes to be introduced on production vehicles were expected to provide additional protection. In addi-

EFV: Lightweighting for an Emerging Threat

The considerable effort made to lightweight the expeditionary fighting vehicle throughout its development nonetheless fell short of the breakthrough strategies needed for the EFV to achieve its objectives. Lightweighting strategies need to keep pace not only with the development cycle but also with the performance needed to face emerging or unknown threats.

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[36] R. O'Rourke. 2011. "Navy Littoral Combat Ship (LCS) Program: Background, Oversight Issues, and Options for Congress." RL33741. Congressional Research Service. April 29.

[37] C.P. Cavas. 2010. "Navy Awards LCS Deals to Lockheed, Austral." *Navy Times*. December 26. Available at http://www.navytimes.com/news/2010/12/navy-awards-lcs-contracts-to-lockheed-martin-austal-122910w/. Last accessed May 18, 2011.

[38] M. Collette. 2011. "Hull Structures as a System: Supporting Lifecycle Analysis." *ASNE [American Society of Naval Engineers] Day 2011 Proceedings.* Available at http://www.navalengineers.org/publications/symposiaproceedings/Pages/ASNEDay2011Proceedings.aspx.

[39] U.S. Government Accountability Office. 2010. *Expeditionary Fighting Vehicle (EFV) Program Faces Cost, Schedule, and Performance Risks.* GAO-10-758R Defense Acquisitions. July.

FIGURE 3-8 Littoral combat ship trimaran (Austal USA–left) and monohull (Lockheed Martin–right). SOURCE: CAPT Mike Good, Program Manager LCS Mission Modules, “Littoral Combat Ship (LCS) Program Overview,” Northwest Florida Defense Coalition, May 14, 2009.

tion, the ONR ManTech program developed a composite forward ramp with integral blast protection to alleviate the need to add aluminum appliqué as a kit once the EFV reaches shore.[40]

The GAO report also noted that difficulties meeting vehicle weight requirement resulted in: reduction in high-speed transit sea state capability from 3 ft to 2 ft significant wave height; proposed removal of integrated nuclear, biological, and chemical protection; and reduction in required vehicle land range following amphibious landing.

Although the Marines had planned to procure 600 EFVs, the program was canceled in early 2011 for budgetary and performance reasons.[41] The Secretary of Defense noted that Hezbollah militants struck an Israeli ship in 2006 with a missile that has a range of 75 miles.[42] The evolving threat had outpaced the performance specifications’ the EFV was designed for a 25-mile ocean mission range—and even after transiting this distance from the Seabase it would need to be refueled once ashore.

3.5.4 High-Strength Steel in Aircraft Carriers[43]

The aircraft carrier fleet consists of 10 Nimitz-class ships (CVNs 68 through 77) and the Enterprise (CVN 65), all nuclear-powered. The Gerald R. Ford class carrier (CVN 78) is the successor to the Nimitz class and will replace the Enterprise. The new design allows more frequent sorties and requires almost 800 fewer sailors, which will reduce operating costs. The Navy estimates that the CVN 78 will save $5 billion in life-cycle costs compared with Nimitz-class ships.

The Navy has considered composite construction for portions of the island structure on the CVN 78 aircraft carrier to correct an anticipated high center of gravity and starboard list condition. However, the platform’s shipbuilder believes that the manufacturing technology is not mature enough to incorporate composite construction for the island or in shipboard piping systems. Lightweight steels (HSLA 65 and HSLA 115) have been identified as “critical technologies” for the CVN 78, with the potential to save 700 tons and 175 tons, respectively.

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[40] Ibid.

[41] A good history of the EFV is given in “The USMC’s Expeditionary Fighting Vehicle (EFV),” *Defense Industry Daily*, June 13, 2011, available at http://www.defenseindustrydaily.com/the-usmcs-expeditionary-fighting-vehicle-sdd-phase-updated-02302/, last accessed August 5, 2011.

[42] T.V. Brook. 2010. “Marines Forge Ahead with New Landing Craft.” *USA Today*. May 5.

[43] This section draws on http://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=200&ct=4; and R. O’Rourke, “Navy Ford (CVN-78) Class Aircraft Carrier Program: Background and Issues for Congress,” Congressional Research Service, August 24, 2010.

FIGURE 3-9 Expeditionary fighting vehicle. SOURCE: U.S. Marine Corps. Available at http://www.efv.usmc.mil/.

The Office of Naval Research recently reported that "successful vendor qualification of first article, full-size production plates of HSLA-115 (named for its increased minimum yield strength of 115 ksi), weld qualification evaluations and explosion testing and completion of Material Selection Information (MSI) certification data have been achieved."[44] The project team[45] was able to qualify HSLA-115 using HSLA-100 welding procedures because the higher-strength steel was produced by heat-treating HSLA-100 rather than an initially proposed solution using 10Ni steel.

CVN 78: Adapting a Qualified Material

The time to qualify HSLA 115 was reduced by heat-treating lower-strength steel rather than using a unique steel composition, which would have required a lengthy program to develop and certify welding procedures.

3.5.5 Lightweight Construction Applications at Sea

Sweden's recent LASS project (lightweight construction applications at sea) was aimed at improving the efficiency of marine transport and increasing the competitiveness of the Swedish shipping industry. The target was to accomplish this through the development and the demonstration of practical techniques for using lightweight

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[44] Office of Naval Research. 2009. "HSLA-115 Procured for Fabrication of CVN 78: Will Reduce Top-Side Weight/Lower Center of Gravity." Available at http://www.onr.navy.mil/en/Media-Center/Press-Releases/2009/HSLA-115-Procured-Fabrication-CVN%2078.aspx.

[45] Participants: PEO Aircraft Carriers; Naval Surface Warfare Center, Carderock Division; Naval Sea Systems Command; Northrop Grumman Shipbuilding-Newport News; Navy Metalworking Center; Arcelor-Mittal Steel; DDL Omni Engineering; Puget Sound Naval Shipyard; and Navy Joining Center.

materials for ship construction. The LASS project demonstrated that 30 percent weight saving could be achieved for major structural elements of the maritime platforms shown in Figure 3-10.

The project focused on developing lightweight fire protection systems for aluminum and composite construction. "Typical weight reduction when using aluminum or FRP composites have been over 50 percent compared to a conventional steel design, and cost analysis has demonstrated possible payback times of 5 years or less for the lightweight material investment, primarily through reduced fuel consumption."[46]

LASS: Economic Viability of Lightweight Ships

The accomplishment of the LASS project in fire protection and lightweight deckhouses, among others, reflects a conscientious effort by Scandinavian countries to address the technological challenges and develop commercial opportunities for their lightweight, composite shipbuilding expertise. By maintaining a strong industrial base in marine composite R&D and construction, these countries are able to build lightweight naval vessels more economically.

3.5.6 Joint High-Speed Vessel Based on a Commercial Catamaran[47]

The joint high-speed vessel (JHSV) shown in Figure 3-11 is a commercially designed high-speed catamaran adapted for U.S. Army and Navy requirements. The Australian shipbuilders Austal and Incat both produce fast catamarans that are widely used as commercial ferries. The Army, Navy, and Marine Corps leased catamarans from the two companies before establishing JHSV requirements. The bid was won by Austal USA, Alabama, for 8 ships, though more recent plans call for 18. The JHSV was able to enjoy a compressed procurement schedule because it is not classed as a warship and was considered to be a "non-developmental" item.

The vessels will be used for fast intra-theater transportation of troops, military vehicles, and equipment. Compared with transport by ferry or amphibious shipping, the JHSV does not need a full-service port and can cut the time of transporting a Marine battalion by more than half. The same transport would take 14-17 "lifts" from C-17 aircraft, at about four times the cost of using the JHSV. The ships will be capable of transporting 600 short tons 1,200 nautical miles at 35-45 knots. They will connect to roll-on/roll-off discharge facilities and on/off-loading a combat-loaded Abrams Main Battle Tank (M1A2).[48]

JHSV: Adapting a Commercial Design

The existence of a related commercial product can accelerate military use of lightweighting technology by reducing the time needed for design, manufacturing process development, and qualification. By leasing commercial vessels, the Department of Defense gained experience before procuring the related joint high-speed vessel.

3.5.7 Redesign of the Mark V Special Operations Craft[49]

The Mark V special operations craft (SOC) is a medium-range, high-speed vehicle used to take U.S. Navy SEALs into and out of operations where the threat to these forces is low to medium. "It is also used for limited coastal patrol and interdiction. It is designed to carry 16 fully equipped Navy SEALs through rough seas at speeds of greater than 50 knots to destinations as far as 800 km from their base, on missions lasting as long as 12 hours."[50]

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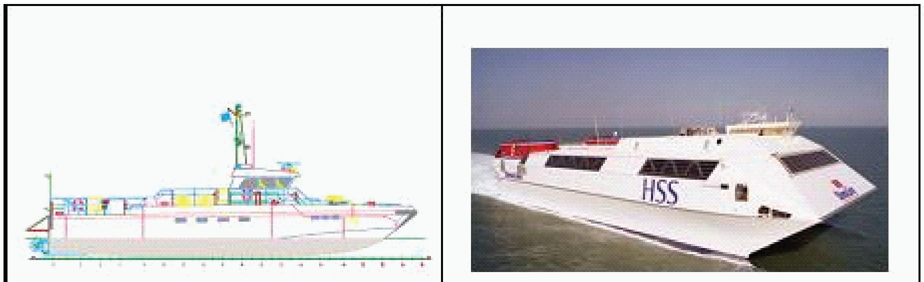
[46] T. Hertzberg. 2009. "LASS, Lightweight Construction Applications at Sea." SP Technical Research Institute of Sweden. March.

[47] This section draws on http://www.defenseindustrydaily.com/jhsv-fast-catamaran-transport-program-moves-forward-updated-01535/ and NAVSEA Public Affairs, "Keel Laid for First Joint High Speed Vessel," July 2010.

[48] NAVSEA Newswire. 2010. "Keel Laid for First Joint High Speed Vessel." July. Available at http://www.navsea.navy.mil/Newswire2010/22JUL10-01.aspx.

[49] This example draws on G. Gardiner, "Composites Take the Hit in U.S. Navy Patrol Boat," *High-Performance Composites*, September 2008; and the "Mark V Special Operations Craft," available at http://discoverspecialforces.com/special-forces-vehicles/mark-v-special-operations-craft/, last accessed October 19, 2011.

[50] G. Gardiner. 2008. "Composites Take the Hit in U.S. Navy Patrol Boat." *High-Performance Composites*. September.



24 m all-composite passenger high-speed craft

88 m aluminum high speed catamaran with an FRP composite superstructure

199 m RoRo vessel with an aluminum deck house

188 m RoPax vessel with an FRP composite superstructure

FIGURE 3-10 LASS project maritime platforms. SOURCE: LASS project. Available at http://www.lass.nu/.

Mark V: A Difficult Balance in Design

The initial Mark V achieved its goals for speed and range through lightweighting, at a cost of frequent injuries to its crew. A lack of robust design tools for the redesign limited the lightweighting potential of carbon fiber construction.

The original competition in 1994 was among three designs: a Kevlar hull, an aluminum monohull, and an aluminum catamaran hull. The contract was awarded to Halter Marine of Gulfport, Mississippi, for its aluminum monohull design. Using an expedited acquisition process, Halter Marine delivered its first Mark V 18 months later, and all 20 were delivered by 1999.

The aluminum Mark V achieved its survivability and performance goals—but was very rough on the warfighters, who experienced excessive fatigue and sustained injuries such as sprained ankles, whiplash, and spinal injuries. "Crews were being subjected to 4- to 5-G impacts one to two times per minute during operations at cruising speed (35 knots) in 3-ft to 4-ft (0.91 m to 1.22 m) waves,"[51] with impacts from larger waves reaching 20 Gs.

The Navy sought to increase comfort for the crews without losing any of the Mark V's performance capabili-

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[51] Ibid.

FIGURE 3-11 Joint high-speed vessel (JHSV). SOURCE: JHSV Technical Brochure, Austal USA, October 2009.

ties. Maine Marine Manufacturing of Portland collaborated with the University of Maine's Advanced Engineered Wood Composites (AEWC) Center (Orono, Maine) under a 4-year contract with the Office of Naval Research to redesign the Mark V using composites and produce a prototype for Navy testing. The lack of robust design tools posed a challenge, which was met in part by AEWC's development of a method for testing wave impact on alternative structures and laminates. According to Maine Marine Manufacturing's president and CEO, David Packhem Jr., the carbon fiber/epoxy resin/foam core Mark V "is actually 50 percent stronger and slightly lighter than its aluminum predecessor, and we expect that Navy testing will confirm that we've been able to reduce transmission of slamming loads."[52] The composite Mark V is shown in Figure 3-12.

3.5.8 Demonstrating the Feasibility and Benefits of the Advanced Enclosed Mast/Sensor System[53]

The Navy's Advanced Enclosed Mast/Sensor (AEM/S) system used innovative materials, structures, and manufacturing techniques, yet it could be produced in a shipyard environment. The system is multifunctional—it encloses a ship's vast array of radars and sensors typically exposed on masts, thus protecting sensors from harsh weather, improving their performance, and reducing the need for maintenance. It is designed to be detachable so that it can be easily replaced by the next generation. The composite AEM/S structure reduces the ship's radar signature and its weight. The faceted nature of the AEM/S structure provides the necessary flat sur-

AEM/S: Lightweight, Multifunctional, Detachable

The AEM/S is a large composite structure that forced the development of analytical methods, structural details, and joining technology. The advanced technology demonstration process allowed the Navy to work in close partnership with the fabricator to develop the new technology that made the AEM/S possible.

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[52] Ibid.

[53] This example draws on J.H. Meloling, 2001, "Advanced Enclosed Mast/Sensor (AEM/S) System," *SSC San Diego Biennial Review,* August; and USSNY website, http://www.ussny.org/faq.php.

FIGURE 3-12 Composite Mark V special operations craft. SOURCE: Available at http://hodgdondefensecomposites.com/projects.shtml.

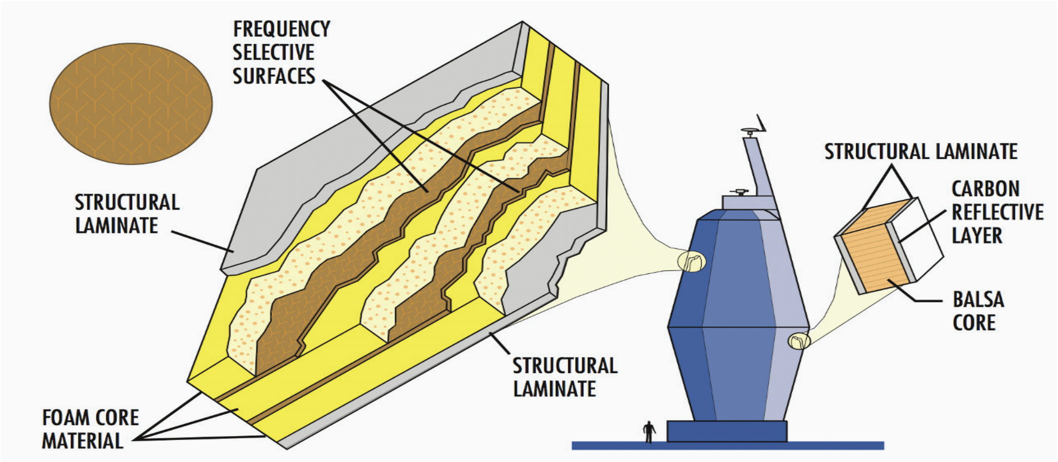

FIGURE 3-13 AEM/S sandwich construction concept. SOURCE: Schematic from Northrop Grumman in J.H. Meloling, "Advanced Enclosed Mast/Sensor (AEM/S) System," *SSC San Diego Biennial Review,* August 2001.

FIGURE 3-14 The *Visby* class corvette. SOURCE: Photo by Kockums AB, "The VISBY Class Corvette: Defining Stealth at Sea," 2006. Available at www.kockums.se.

faces for mounting phased array antennas. Figure 3-13 shows how frequency selective surfaces are used to control what signals are transmitted through the structure.

The AEM/S was fielded as an advanced technology demonstration (ATD) on the on the USS Arthur W. Radford (DD 968) in 1997. It survived 100-mph-plus winds and an accidental ship collision, and demonstrated the ability to design and fabricate enclosed mast structures for Navy ships. The AEM/S is now the baseline design used on the LPD (Landing Platform Dock)-17 class of ships.

3.5.9 Lack of Domestic Production Capability for the Fast Response Cutter

FRC: Technology Transfer Failure

Despite a partnership between the Swedish company Kokums, builder of the *Visby* class FRC, and Northrop Grumman Shipbuilding, design problems in the United States caused the planned technology transfer to fail. As a result, the United States has no organic capability to build lightweight composite warships. An understanding of what went wrong might help avert such problems in the future.

The *Visby* class ship was developed by the Swedish Navy as a fast, stealthy corvette that could serve the extensive littoral areas of Sweden. The *Visby* was designed by the Kokums Karlskrona shipyard using carbon fiber/vinylester/foam core construction to achieve her lightweight and stealth objectives. Shown under way in Figure 3-14, the *Visby* is 73 meters long and displaces 640 tons fully loaded. The hull structure was built by carefully joining panels that were fabricated on a flat table. Kokums and Northrop Grumman Shipbuilding were engaged in a technology transfer partnership for a short period of time, but no *Visby* vessels were ever built in the United States. The U.S. program was suspended after numerous concerns were raised.[54]

3.6 CONCLUSIONS

All ships benefit from lighter-weight construction, which increases payload capacity, range, and fuel economy. At present, cost and survivability are the overriding factors constraining further use of lightweight materials on military maritime platforms. The committee reached the following conclusions about lightweighting maritime platforms:

- The impetus for lightweighting smaller ships and boats is either to meet speed targets or to meet an imposed transportability requirement.
- Larger ships look to lightweighting primarily to improve stability, which requires reducing weight high in the vessel.
- The cost for lightweighting military ships, and the acquisition time, can be drastically reduced if there is a parallel commercial application for the technology, as indicated in the example of the joint high-speed vessel.
- There is a lot of empirical knowledge of how steel structural details perform over time in an ocean environment. There is less experience with advanced materials, which can lead to conservative designs or in-service failures, such as the wave damage shown in Figure 3-7.
- The United States does not have mid-tier shipyards with experience building military vessels in aluminum or composites and therefore relies on technology transfer for this expertise (recently, Australia for aluminum; Scandinavia for composites; and Italy for high-strength steel).
- Aluminum construction requires attention to alloy selection, structural details, and joining procedures.
- Composite construction requires reliable, sufficient quantities of materials and a focus on material characterization, manufacturing quality assurance, and in-service non-destructive evaluation.
- High-strength steel presents challenges with product sourcing, welding, and distortion control.

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[54] R. O'Rourke. 2006. "Coast Guard Deepwater Program: Background and Issues for Congress." Congressional Research Service. July 1.

- Perceived combat threats and their concomitant vessel requirements are constantly changing, which poses a challenge to a 10- to 20-year design cycle for new technology integration on ships that often are expected to last 40 years.
- The design process for U.S. Navy ships is extremely risk averse, with little reward for performance improvement and extreme financial penalties for structural failures.
- Many factors—the difficulty of anticipating future threats, the limitations of cost models, and the desire to keep costs down in the near term—make it extremely difficult to buy ships based on life-cycle considerations.
- By virtue of their size, large ships put a premium on material cost and joining technology.
- Lightweighting technologies are generally developed on smaller craft (often recreational racing boats) that have shorter development cycles and place a premium on performance.

4

Lightweighting Land-Based Vehicles

4.1 CURRENT STATE OF LIGHTWEIGHTING IMPLEMENTATION AND METRICS

4.1.1 Drivers of Lightweighting

Lightweighting of land-based vehicles has been a strategic focus of the U.S. military for decades. The principal drivers for lightweighting are as follows:[1,2]

- Increased protection and survivability of personnel and vehicles, enabled by a re-allocation of material weight in non-protective functions into enhanced armor systems;
- Reduced costs of operation, extended vehicle range, and reduced needs for in-theater transportation of fuels resulting from improved fuel efficiency of lighter vehicles;
- Increased vehicle mobility, agility, payload and speed as well as greater flexibility of operations over a wider range of terrains; and
- Improved transportability and speed of force deployment enabled by reduced vehicle weight.

4.1.2 Historical and Current Lightweighting

Lightweighting in land-based vehicles has been achieved principally by replacing steels with high-strength aluminum alloys and, more recently, titanium. Numerous examples of successful, economical vehicles of aluminum construction are found over the past half-century. Tracked combat vehicles offer more opportunity and greater performance benefits—particularly where protection is concerned—than the naturally lighter support vehicles. Hence, despite the far greater number of the latter, the chapter focuses on heavy combat vehicles.

Use of aluminum alloys in tactical land-based vehicles has not been restricted to the United States. These alloys have also been employed on the hull and turret of the BMP-3 (nicknamed Troyka) one of the most heavily

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[1] D. Gorsich, Chief Scientist, Tank Automotive Research, Development & Engineering Center (TARDEC), "Overview: Military Ground System Material Needs," presentation to the committee, 2010.

[2] NRC. 2003. *Use of Lightweight Materials in 21st Century Army Trucks.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10662.

FIGURE 4-1 A warrior vehicle with added reactive appliqué and bar-armor. SOURCE: BAE Systems, U.S. Combat Systems, “Lightweighting in Military Vehicles,” presentation to the committee, December 8, 2010.

armed infantry combat vehicles of the Soviets.[3] They have also been used on the FV 510 Warrior Infantry Section Vehicle, built in the United Kingdom. The latter was constructed of an aluminum alloy hull and equipped with additional appliqué armor as well as explosive-reactive armor and bar armor (Figure 4-1). The efficacy of the protection system against small arms, missiles, rocket propelled grenades, and anti-tank mines was proven during the United Nations operations in Bosnia.[4]

Despite the performance enhancements obtained from the use of aluminum alloys in structural components of ground vehicles, their use in *armor systems* for tactical vehicles has met with mixed success.[5] The difficulty of using aluminum alloys in armor can be attributed at least in part to an inadequate understanding of the ballistic and blast properties of these alloys over the pertinent threat range. The ballistic properties are better understood than blast properties; however, the modeling of both types of threats is insufficient for the predictive modeling and systems-level design for performance across the full spectrum of current threats from improvised explosive devices (IEDs), explosively formed projectiles (EFPs), and other sources.

Recent aluminum-alloy developments have led to further improvements in ballistic resistance and durability. For instance, Al 2519-T87 (MIL-DTL-46192) exhibits better performance against fragmentation threats than Al 5083, with nearly the same performance against ball and armor piercing threats as Al 7039, coupled with good corrosion resistance. The first production utilization of this alloy will be the Marine Corps Expeditionary Fighting Vehicle.[6]

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[3] For information on BMP-3 specifications, see http://www.army-technology.com/projects/bmp-3/specs.html and http://www.army-technology.com/projects/bmp-3/, last accessed October 19, 2011.

[4] Christopher Foss and Peter Sarson. 1994. *Warrior Tank Specifications: Warrior Mechanised Combat Vehicle 1987-1994*. New Vanguard Series No. 10. London: Osprey. Available at http://www.army-technology.com/projects/warrior/.

[5] Much of the information on lightweighting armor systems for land vehicles using materials other than aluminum is either restricted or classified and therefore is not included in this report.

[6] “Army Materials Research: Transforming Land Combat Through New Technologies.” *AMPTIAC [Advanced Materials and Process Technology Information Analysis Center] Quarterly,* Vol. 8, No. 4, 2004. Available at http://ammtiac.alionscience.com/pdf/AMPQ8_4.pdf.

Present Status

The Army has not fielded any new major combat platforms for over 20 years. Some of its early lightweighting successes still see combat. Section 4.5, which describes examples of lightweighting vehicle systems, begins with three such successes: the M113 Armored Personnel Carrier, the M551 Sheridan Light Tank, and the Bradley Fighting Vehicle.

That does not mean that the Army no longer has interest in lightweighting. On the contrary, over the past two decades it has launched five separate programs that prominently featured lightweight designs—none of which has reached production and integration into the battlefield. The difficulties facing these programs offer lessons for future lightweighting efforts. Two of these canceled programs are described in Section 4.5: the XM2001 Crusader 155mm Self-Propelled Howitzer and the Future Combat System.

4.1.3 Current State of Metrics

Unlike the aircraft industry, where the metrics for lightweighting are well established and feature prominently in the earliest stages of the design process, a comparable set of quantitative metrics appears not to exist in the ground vehicle community. Designs are usually constrained by overall vehicle weight, typically set to meet air transportability requirements. Weight savings that may be achieved through use of low-density materials or clever lightweighting designs are parlayed into weight additions elsewhere in the vehicle, to enhance functionality, e.g., increased protection against evolving threats, such as those encountered in Iraq and Afghanistan. Hence there does not appear to be a well-defined or overarching metric that characterizes "the value of a pound saved."

In some respects, lightweighting may appear to be antithetical to the goal of warfighter protection. Historically, the level at which vehicle requirements—protection and otherwise—have been met correlates strongly with overall vehicle weight. That is, heavier classes of combat vehicles generally meet more requirements and to a higher degree than those in the lower weight classes (Figure 4-2). But these improvements invariably come at the

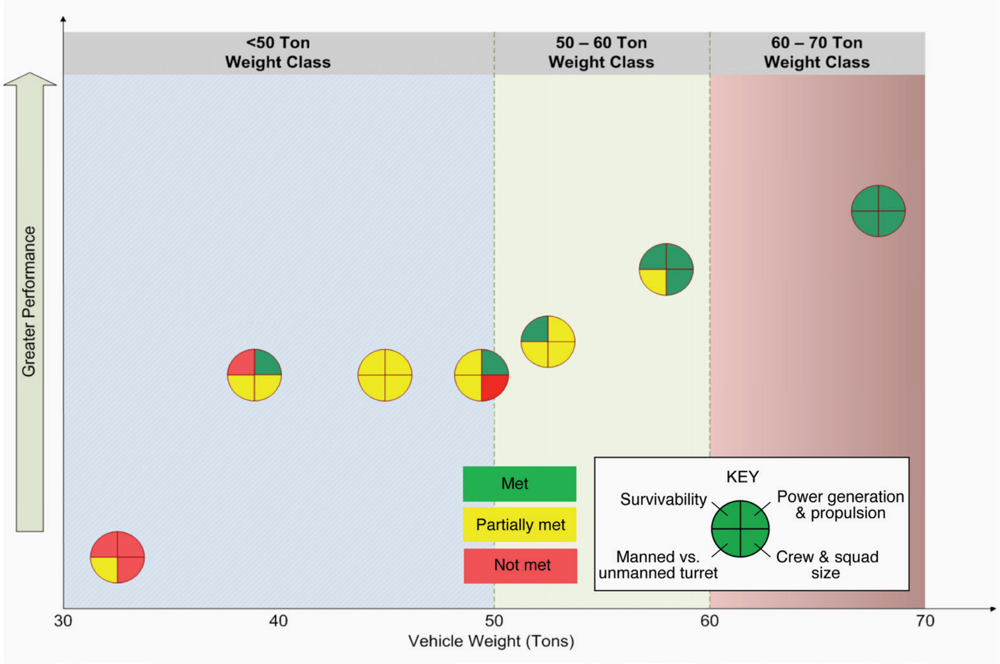

FIGURE 4-2 Tradeoffs between combat vehicle weight and achievement of performance requirements. SOURCE: Adapted from BAE Systems, U.S. Combat Systems, "Lightweighting in Military Vehicles," presentation to the committee, December 8, 2010.

expense of reduced fuel economy, mobility, and speed. The broad trend (especially with respect to survivability) reflects to some extent the additional armor afforded to heavier vehicles. In principle, lightweighting could have beneficial effects on these attributes without necessarily compromising protection. As noted in Chapter 1, lightweighting can help to balance the "iron triangle" of performance, protection, and payload.

The challenge stems from the fact that, for a prescribed dynamic load (from a buried mine explosion, for example), the acceleration of the vehicle scales inversely with its mass. This, in turn, has important implications in the potential threat to the vehicle occupants. Clearly, this is a feature that does not derive benefit from lightweighting. Thus, lightweighting might in some circumstances be viewed as a strategy for reducing weight in one component in order to increase survivability by adding weight to a different component.

4.2 BARRIERS AND KEYS TO SUCCESS

4.2.1 Technological Challenges

Materials

Achieving protection goals while holding down costs is a continual challenge. In armor systems, significant weight reductions can be achieved through the replacement of armor steels with advanced aluminum alloys, composites, ceramics, and expanded steel. But the weight reductions come at the expense of higher cost (for examples, see Figure 4-3). In principle, even greater reductions could be achieved through the use of detection avoidance technologies and active protection systems.

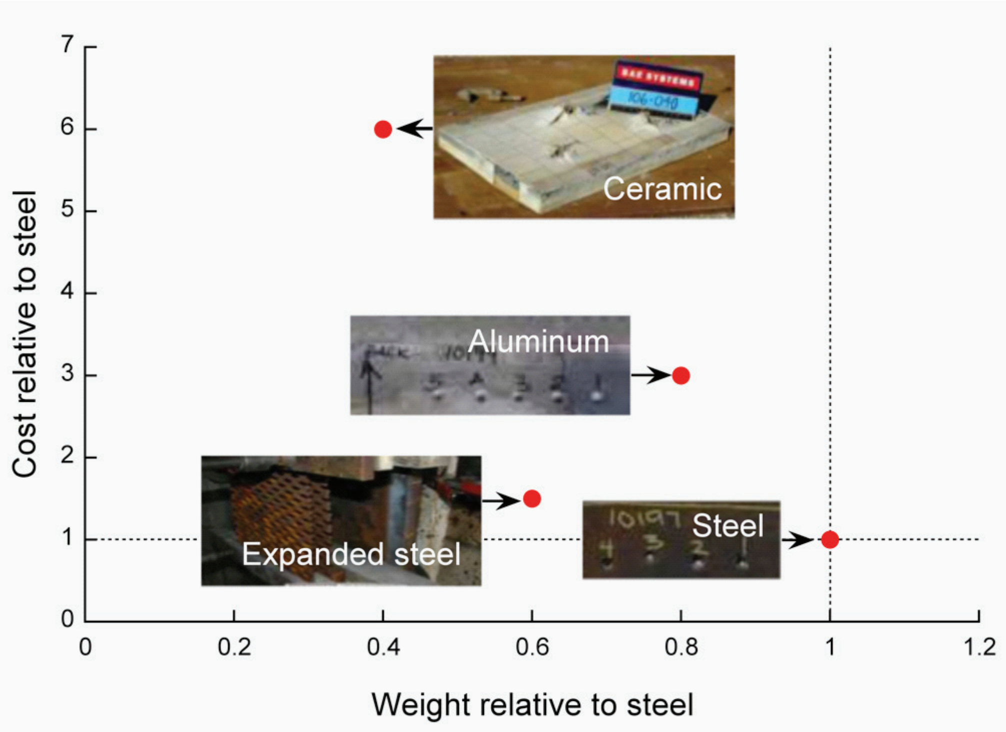

FIGURE 4-3 Tradeoffs between weight reduction and cost for some candidate materials systems used in armor systems. SOURCE: Adapted from BAE Systems, U.S. Combat Systems, "Lightweighting in Military Vehicles," presentation to the committee, December 8, 2010.

Other structural materials, notably magnesium and titanium alloys, offer large potential advantages over steels, including higher specific strength, absence of low-temperature embrittlement, and greater structural rigidity resulting from thicker sections. Titanium also exhibits superior corrosion resistance in most service environments, yet the utilization of these materials remains rare. Numerous barriers exist to their exploitation. Chief among them are cost and domestic availability:

- The cost of extraction of raw titanium is inherently high. The current price of titanium in ingot form is approximately $20/lb. Steels, in contrast, cost between $0.50 and $3.00/lb depending on alloy and product form. Magnesium is significantly cheaper than titanium, with a current price of approximately $2/lb. For land structures, most applications of titanium and magnesium would be in the form of sheet and plate. The complexity of forming titanium and magnesium alloys into useful engineering shapes coupled with their low production volumes exacerbate the price differentials with the baseline steels.[7]
- Domestic availability and sheet/plate manufacturing capacity of magnesium and titanium alloys are far below the large-tonnage requirements of targeted land-based military vehicle applications.

Additional (secondary) considerations include the following:

- Welding is the most economical way to join materials in producing large structures with good mechanical integrity. It is also the principal route for producing water-tight structures (e.g. amphibious vehicles). The weldability of titanium and magnesium alloys remains problematic in routine industrial practice in land-based vehicles.
- Monolithic aluminum, magnesium, and titanium alloys exhibit inferior spall resistance relative to steels.[8] They may also exhibit inferior service lives due to lower fatigue resistance as well as susceptibility to corrosion in marine environments.
- There is an understandable reluctance within the DOD and its suppliers to transition to new materials that are not supported by comparable levels of experience in manufacturing, assessment of battlefield damage, and in-field repair.

New Designs

Some intriguing new designs for vehicles are emerging that offer promise for greater protection without adding more armor weight. One approach for military trucks is to "vent" the dynamic load (explosive force) up through a channel in the vehicle as if through a chimney to reduce the coupling of the blast loading to the vehicle.[9] As reported in the *New York Times*, "if the final tests go well, the invention could save billions in new vehicle costs and restore much of the maneuverability that the Army and the Marines have lacked in the rugged terrain in Afghanistan, military officials say."[10]

Another approach is to adapt the V-hull design used in mine-resistant trucks into a double V-hull for the Army's Stryker Brigade Combat Vehicle. The recent award of a contract to build 450 double V-hull Stryker vehicles comes in response to the need to counter the increasingly deadly threats experienced in Afghanistan from roadside

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[7] For more information on forming titanium and magnesium alloys, see http://www.metalprices.com/FreeSite/metals/ti/ti.asp and http://www.metalprices.com/freesite/metals/Steel/Steel.asp. Last accessed October 19, 2011.

[8] BAE Systems, U.S. Combat Systems, "Lightweighting in Military Vehicles," presentation to the committee, 2010; and "Army Materials Research: Transforming Land Combat Through New Technologies," *AMPTIAC [Advanced Materials and Process Technology Information Analysis Center] Quarterly,* Vol. 8, No. 4, 2004, available at http://ammtiac.alionscience.com/pdf/AMPQ8_4.pdf.

[9] Grace V. Jean. 2011. "Double V-Hulls, Chimneys, Seen as Viable Alternatives to Armor." *National Defense*. March. Available at http://www.nationaldefensemagazine.org/archive/2011/March/Pages/ DoubleVHullsChimneysSeenAsViableAlternativestoArmor.aspx.

[10] Christopher Drew. 2011. "Revamped Humvee Draws Military's Eye." *New York Times*. July 22. P. B1. Available at http://www.nytimes.com/2011/07/23/business/humvee-with-chimney-for-safety-draws-militarys-interest.html. Last accessed October 19, 2011.

FIGURE 4-4 Three joint light tactical vehicle prototypes. SOURCE: S. Magnuson. 2010. "New Truck to Show the Way for Acquisition Reforms." *National Defense Magazine*. August.

bombs.[11] Improved vehicle survivability in this evolving production and upgrading of vehicles will be accomplished by added armor and alterations in design approaches.[12]

4.2.2 Reducing the Acquisition Cycle

The technological challenges are exacerbated by a protracted acquisition process during which the vehicle requirements often "creep." That is, various DoD agents sequentially add requirements from the time of initial design to that of vehicle production and delivery. Without knowledge of the full spectrum of expected requirements of the vehicles at the outset, defense contractors are naturally disinclined to replace existing materials with new ones. The risk is that deficiencies in material performance may not emerge until late in the design and manufacturing stages, wherein the full spectrum of requirements becomes known.

Attempts at accelerating the process through competitive prototyping—a process in which two or more defense contractors produce competing prototypes—have met with mixed success.[13] Its underlying rationale is that forcing the manufacturers to use proven technologies will discourage the later introduction of new and untested components; as a result, competitive prototyping is expected to reduce the risk of cost overruns and failure for military hardware development programs. It has been adopted as a mandatory requirement in DOD Instruction 5000.2, updated in December 2008.

In a recent example of competitive prototyping, three vendors—BAE Systems, Lockheed Martin, and a consortium of AM General and General Dynamics Land Systems—produced a total of 21 prototypes (Figure 4-4) for the Joint Light Tactical Vehicle (JLTV) program, which is intended to replace some Humvees (HMMWVs—High-Mobility Multipurpose Wheeled Vehicles). Testing of these prototypes began in August 2010. The initial promise of this endeavor faded, as Mark McCoy, the Army's JLTV product manager, reported in February 2011 that every prototype design was between a few hundred and 1,000 lb too heavy to be airlifted by a CH-47 Chinook helicopter.[14]

The JLTV was intended to meet the needs of the Army, which placed greater emphasis on protection, and the Marine Corps, which gave higher priority to lightweighting. Attempting to satisfy both sets of requirements simultaneously is likely the reason that the 21 JLTV prototypes failed to meet weight specifications, resulting in

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[11] Grace V. Jean. 2011. "Double V-Hulls, Chimneys, Seen as Viable Alternatives to Armor." *National Defense*. March. Available at http://www.nationaldefensemagazine.org/archive/2011/March/Pages/ DoubleVHullsChimneysSeenAsViableAlternativestoArmor.aspx.

[12] Christopher Drew. 2011. "Revamped Humvee Draws Military's Eye." *New York Times*. July 22. P. B1. Available at http://www.nytimes.com/2011/07/23/business/humvee-with-chimney-for-safety-draws-militarys-interest.html. Last accessed October 19, 2011.

[13] This section draws on S. Magnuson, 2010, "New Truck to Show the Way for Acquisition Reforms," *National Defense Magazine*, August, available at http://www.fas.org/sgp/crs/natsec/RL34026.pdf; and E. Beidel, 2011, "Challenges Remain as JLTV Competition Heats Up," *National Defense Magazine*, May.

[14] Reported at the National Defense Industrial Association's Tactical Wheeled Vehicle conference, February 2011, and reported in E. Beidel, 2011, "Challenges Remain as JLTV Competition Heats Up," *National Defense Magazine,* May.

a delay in finding a satisfactory "trade" between protection and weight-related performance characteristics for light tactical wheeled vehicles.

The JLTV prototype experience suggests the desirability of finding ways to increase the probability that prototypes will meet requirements. For example, instead of discovering during prototyping how new materials and new designs for lightweighting affect other attributes, it would improve the chances of detecting and addressing problems to test new technologies earlier in the acquisition process. For example, perhaps a precursor demonstration step could try out new materials and new designs for lightweighting in terms of their effects on other attributes before a prototype is developed.

The Weapons System Acquisition Reform Act of 2009 requires that competitive prototypes be produced for major weapons acquisition programs prior to Milestone B, which is when independent review boards decide whether the program can proceed to the engineering and manufacturing development (EMD) phase.[15] Under some circumstances competitive prototyping may be waived, in which case only one prototype is required. Nonetheless, it appears that the Army has been able to waive even the single prototype requirement prior to EMD as evidenced by JLTV program. Specifically, a recent JLTV vehicle update stated:

> The Government has made a determination to NOT require the delivery of a demonstrator vehicle during the EMD RFP proposal phase. Due to evolving EMD requirements, it is assumed that any demonstrator vehicle built to currently available draft RFP requirements will not be reflective of the final RFP requirements for EMD.[16]

The Army's decision is based on the expectation that the requirements will change, but it has the added benefit of providing more time to validate the technology before building a prototype.[17]

4.3 LIGHTWEIGHTING OPPORTUNITIES FOR LAND-BASED VEHICLES

Lightweighting of land-based vehicles remains a clear strategic focus of the DoD.[18] Indeed, with the escalation in "scope growth and requirements creep"—that is, the expansion of the requirements of a single vehicle in order to meet a multitude of mission types and increased operational performance, such as increased warfighter protection, increased vehicle range, and reduced energy utilization, while minimizing development and production costs of multiple vehicle variants—the need for lightweighting is arguably more acute than ever.

Numerous opportunities exist to improve tactical utility of future military vehicles through lightweighting. Bringing them to fruition will require long-term commitments and coordinated multi-agency strategies. Specific opportunities and strategies for their successful implementation follow.

4.3.1 Systems Engineering

As described in Chapter 2 (Air), systems engineering is a strategy for considering the many elements of a complex system early in the design and acquisition of that system. Bringing together experts knowledgeable about diverse aspects of the system—components, design, manufacturing, performance, cost, etc.—the risk of discovering

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[15] Weapon Systems Acquisition Reform Act of 2009, 111th Congress, S. 454, Sec. 203, available at http://www.gpo.gov/fdsys/pkg/BILLS-111s454enr/pdf/BILLS-111s454enr.pdf.

[16] For more information on the Joint Light Tactical Vehicle (JLTV) EMD Phase, see http://contracting.tacom.army.mil/majorsys/jltv_emd/jltv_emd.htm, last accessed September 28, 2011.

[17] While considering next steps for the JLTV, the Army is also pursuing the Humvee Recap, intended to add protection to the Humvee while maintaining or reducing weight. See Grace V. Jean, "Humvee Recap Competition Heating Up," *National Defense*, October 2011, available at http://www.nationaldefensemagazine.org/archive/2011/October/Pages/HumveeRecapCompetitionHeatingUp.aspx. It was beyond the committee's scope to address the choices among lightweight tactical land vehicles; the JLTV is described to illustrate competitive prototyping and the difficulty of meeting different needs simultaneously.

[18] NRC. 2003. *Use of Lightweight Materials in 21st Century Army Trucks*. Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10662. Last accessed October 19, 2011.

deficiencies later in the process is reduced. Within the Army, TARDEC takes the lead on systems engineering for ground vehicles.[19] The last example in Section 4.5 is the successful use of systems engineering in the Ford F-150.

4.3.2 Virtual Prototyping

The computing power available to the DOD is tremendous. It should enable increased use of virtual prototyping and increased emphasis on system design, in part to allow early assessment of the tradeoffs in lightweighting strategies. This goal will require integration of shared models of materials, processes and performance between vendors and original equipment manufacturers (OEMs). Virtual prototyping would also have the desirable effect of compressing the acquisition cycle.

As suggested under "Competitive Prototyping," ways of increasing the probability that prototypes will meet requirements may be available. Virtual prototyping could play an important role in assessing new materials and new designs for lightweighting in terms of their effects on other attributes. The design solutions that look the most favorable could then progress to the physical prototyping stage.

4.3.3 New Computational Tools

The success of virtual prototyping and system design is predicated on the availability and use of high-fidelity computational tools for describing the loads imparted by specific enemy threats, e.g., kinetic energy penetrators, shaped charges, EFPs, and IEDs, as well as the response of materials and structures under those loads. Although significant progress has been made on this front over the past decade, striking deficiencies are evident and require remediation. Specifically, there is a need to develop a better understanding of the physics and mechanics of plastic flow, damage evolution and material rupture under extreme dynamic environments. Effects of microstructural heterogeneities in single- and multiphase systems, processing history and probabilistics need to be considered as well. Additionally, codes that integrate multi-physics phenomena and multiple length scales are required. There are also deficiencies in commercial finite element codes in accurately capturing the coupling between dynamic loads and structural response. The opportunities for potentially fruitful research areas include extended finite element codes, particle-based numerical methods, and adaptive physics models.

4.3.4 Lightweight Materials

A number of relatively lightweight materials such as titanium, magnesium, and structural composites show outstanding potential for lightweighting and for expanding the capabilities of military vehicles. But in many instances the implementation of these materials is hampered by their high costs, low technology or manufacturing readiness levels, and limited domestic availability. Capitalization of these opportunities will require a federal investment strategy to identify the materials that are of greatest strategic value to the DOD, seek lower-cost production routes, and increase the domestic processing capacity and manufacturing readiness levels.

One way to facilitate the introduction of lightweight materials is through increased utilization of the same materials in industrial sectors such as transportation, aerospace, energy security, and power generation. For example, the materials requirements for heavy wheeled equipment and trucks have many potential parallels with land-based military vehicles. In this context, it is important to note that the National Automotive Center (NAC) at TARDEC has the mission to identify and develop dual-use technologies for land-based vehicles between DOD and the automotive industry.

Recent advances in the synthesis of titanium alloy powders by direct reduction methods (meltless titanium) have led to new opportunities to produce titanium alloys with enhanced capabilities at lower cost.[20]

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[19] John Wray. 2010. "'Insight, Not Just Oversight'—Following DOD Lead, Embedded Systems Engineering Provides the Framework for Solid Decision." *Accelerate* magazine, Summer, p. 10. Available at http://tardec.army.mil/Documents/TARDEC_0910_accelerate_Summer_2010.pdf.

[20] A. Woodfield, E. Ott, J. Blank, M. Peretti, D. Linger, and L. Duke. 2009. "Meltless Titanium—A New Light Metals Industry." *Materials Science Forum*, Vols. 618-619, pp. 135-138.

4.3.5 Standardization in Vehicle Design

The success of military vehicles is predicated on the alignment of their capabilities with mission requirements. The recent historical experience has been that enemy threats and the associated mission requirements have evolved more rapidly than the corresponding capabilities, especially with regard to protection systems. This disparity requires not only close scrutiny of the threats that are likely to be faced in the future (a challenging task that is undoubtedly being tackled by the DOD) but also emphasis on the adaptability of fielded systems to meet the evolving threats. Commonality and standardization in vehicle design may help to improve in-theater upgrading, facilitate repair, and reduce costs and acquisition times.

4.3.6 Other Emerging Technologies

Among the emerging structural concepts for lightweighting, high-strength "expanded steel" for use in armor systems shows promise. Concepts that enable multi-functionality, e.g., by combining structural functionality with personnel and cargo protection, are also worth pursuing.

It would appear that there are also opportunities for very significant reductions in the weight of protection systems through emerging detection avoidance and active protection technologies. Identifying revolutionary or game-changing strategies to protection could reduce the needed armor, with major lightweighting benefits..experience of the Future Combat System (see Section 4.5.5) might offer some lessons.

Development and use of materials and design tools for lightweighting of land-based military vehicles will be a source of information and tools for the automotive industry, which has been striving to reduce the weight of vehicles without compromising other attributes that consumers value.

4.4 LONG-TERM CONCERNS IN LIGHTWEIGHTING LAND-BASED VEHICLES

A National Research Council report,[21] written and released in 2003, concluded that cost was the principal factor driving the design of Army vehicles. Almost immediately thereafter, the start of the U.S. conflicts in Afghanistan and Iraq meant that U.S. troops were actively engaged in combat. The current view from all levels within the DoD appears to be that, with troops presently in combat and considering the heavy casualties incurred over the past 8 years, protection is the preeminent driver of vehicle design. It would not be unexpected, however, to see the pendulum swing back—wherein greater focus is directed at cost rather than principally protection—once active conflicts have ended and the immediate risks to warfighters have seemingly dissipated. Balancing these competing drivers of design in a changing environment is a never-ending issue.

Implementation of lightweighting strategies will require a multi-pronged approach involving not only scientific discovery and technology development but also coordinated federal strategies and policies. Perhaps the largest barrier stems from the broad perception that the fields of structural materials and manufacturing are sufficiently mature so as to warrant only minimal research support and development. Indeed, the past two decades have seen a dramatic decline in funding in these areas. It seems likely that further progress in lightweight structural materials and their associated manufacturing processes will be incremental and slow.

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[21] NRC. 2003. *Use of Lightweight Materials in 21st Century Army Trucks.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10662.

4.5 EXAMPLES OF LIGHTWEIGHTING IN LAND-BASED VEHICLES

4.5.1 M113 Armored Personnel Carrier

The M113 Armored Personnel Carrier (APC)[22] was introduced in 1960 to transport infantry forces across a hostile battlefield. Lightweighting helped the M113 APC revolutionize mobile military operations; it was air-transportable, air-droppable, and capable of amphibious operation in lakes and streams, cross-country travel over rough terrain, and high-speed travel on pavement. These features allowed the M113 to be deployed in a wide range of combat situations and rapid-deployment scenarios.

M113: Lightweighting When Survivability Is Primary

The many variants in the M113 family of vehicles illustrate that effective lightweighting can be used to retain performance characteristics while improving survivability.

The U.S. Army was the first service to use aluminum as an armor material in armored transport vehicles and offensive weapon vehicles. The original M113 was built of aircraft-quality[23] Aluminum 5083—an alloy that possesses strength approaching those of some steels at only about one-third the weight. The hull armor was also made from Aluminum 5083.

The M113 has been remarkably successful; about 80,000 M113-based systems have entered service in more than 50 countries. It became the basis for a family of vehicles produced in about 40 variants, with many times that number of minor field modifications. With updating and reconfiguring, M113s are still being produced and fielded today.

The M113 was conceived as a "battle taxi" that would carry infantry to the battlefield, where they would fight on foot. Early in the Vietnam War, this approach resulted in high casualties for the Army of the Republic of Vietnam (ARVN), as they dismounted into knee-deep water where they were vulnerable to enemy fire. Thereafter, the ARVN ignored U.S. doctrine and remained inside the M113. While the Aluminum 5083 armor in the M113 stopped small arms bullets and shell fragments, it did not stop rocket-propelled grenades or provide adequate protection against mine blasts detonated under the vehicle. In 1965, the ARVN modified the M113 by expanding from one exposed machine gun to three machine guns, all protected by armor; this version was the first armored cavalry assault vehicle (ACAV). Starting in 1966, an improved version of the ACAV was deployed in Vietnam by U.S. troops, with further upgrades during the war (Figure 4-5).

A major redesign came in 1987, with the introduction of the A3 version. Spall suppression liners throughout the interior of these vehicles offer greater troop protection by restricting the spread of spall when a round penetrates the hull. A new powertrain provides greater mobility and survivability, while improving fuel efficiency, acceleration, speed, and braking.

The upgrades have increased the weight—the combat weight of the 1960 M113 was 23,520 lb, compared with 27,200 lb for the A3. As a result, the A3 was given a more powerful engine, which offered the ability to add hardened steel side armor, a "slat armor" cage, and additional anti-mine armor on the vehicle underbelly. Although the armor increases the weight to 31,000 lb, the use of lightweighting techniques has made it possible for the A3 to have the desired performance and survivability attributes.

While the U.S. Army returned to the single machine gun M113 after the Vietnam War, the Israeli Defense Force (IDF) embraced the idea of the ACAV and still uses it today. Its version is protected by a "skirt" of lightweight sheets of perforated steel, which reduces damage by detonating rocket-propelled grenades before they come into contact with the hull. The IDF tried a variant with explosive reactive armor, but the added weight strained the

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[22] The description of the M113 draws on D. Starry, 1978, "Mounted Combat in Vietnam," Vietnam Studies, CMH Pub 90-17, Department of the Army; S. Dunstan, 1983, *The M113 Series,* London: Osprey; S. Crist, 2004, "M113 APC: Four Decades of Service and Still Showing Potential," *Infantry Magazine*, July-August, available at http://findarticles.com/p/articles/mi_m0IAV/is_4_93/ai_n6362165/; http://www.fas.org/man/dod-101/sys/land/m113.htm; and http://www.army.mil/factfiles/equipment/tracked/m113.html, accessed June 10, 2011.

[23] The development and qualification of aluminum alloys did not progress as quickly for use in land vehicles as for use in aerospace applications.

FIGURE 4-5 M113 armored cavalry assault vehicle in Vietnam. SOURCE: Available at http://en.wikipedia.org/wiki/File:Armored_cavalry_assault_vehicle.jpg.

engine and reduced speed and handling; this variant was discontinued. The IDF is now working on a lightweight but stronger armor made of layers of steel, rubber, ceramics, and explosive reactive armor.

4.5.2 M551 Sheridan Light Tank

The M551 Sheridan Light Tank,[24] shown in Figure 4-6, was an assault vehicle designed in the early 1960s to have both air-drop and swimming capabilities. It saw extensive combat in Vietnam and limited service in Operation Just Cause (in Panama) and Operation Desert Storm (in Kuwait).

The Sheridan Tank was armed with a technically advanced gun that fired conventional ammunition and guided anti-tank missiles. With an aluminum hull and the first use of spaced aluminum armor, it was at the time a unique approach to lightweighting. Equipped with a relatively powerful 300 hp diesel engine, the M551 was exceptionally fast. It was airdrop-capable and fully amphibious, but these advantages of light weight came at a cost.

In its first combat mission, the Sheridan drove over a mine, which ruptured its hull and then ignited the ammunition of the main gun, causing an explosion that destroyed the tank. The aluminum armor could be pierced not just by under-belly mines but also by heavy

M551: Improved Performance, Decreased Survivability

The M551 illustrates the mixed success experienced in replacing steels with aluminum alloys in military vehicles for which survivability and performance are both important. The specific approaches to lightweighting the M551 created vulnerabilities.

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[24] The description of the M113 is based on D. Starry, 1978, "Mounted Combat in Vietnam," CMH Pub 90-17, Vietnam Studies, Department of the Army; R.P. Hunnicutt, 1995, *Sheridan: A History of the American Light Tank,* Vol. 2, Presidio Press; and http://www.army-guide.com/eng/product3393.html.

FIGURE 4-6 M551 Sheridan tank. SOURCE: BAE Systems, U.S. Combat Systems, "Lightweighting in Military Vehicles," presentation to the committee, December 8, 2010.

machine-gun rounds as well. Its 152mm gun was too big for the lightweight chassis, causing the entire vehicle to recoil with great force when the gun was fired. Field commanders commonly added a large steel shield around the gun for protection while firing it. The Sheridan was good at opening bamboo thickets, but not at breaking through dense jungle. Thus, although the Sheridan had greater mobility, firepower, range, and night-fighting ability than its predecessor, its deficiencies led to heavy Sheridan losses in Vietnam and Cambodia.

The Army began to phase out the Sheridan in 1978; however, the 82nd Airborne Division retained its until 1996 because the Sheridan was the only air-deployable tank in its inventory. The Sheridan tanks were upgraded with a thermal sighting system and were used successfully in Operation Just Cause and Desert Storm.

4.5.3 Bradley Fighting Vehicle

The Bradley Fighting Vehicle[25] was originally designed as an APC and a tank-killer. Its main task was transporting infantry with armor protection while providing covering fire to pin down enemy troops. The new Bradley was designed to keep up in formation with M1 Abrams battle tank. This allowed the two vehicles to maintain formations while moving, something that the older M113 could not do as it had been designed to complement the M60 Patton.

The Bradley, shown in Figure 4-7, had a hull base made from Al 5083-H131 (MIL-DTL-46027), and the upper half of the vehicle employed Al 7039-T64 (MIL-DTL-46063). In service, the 7039 alloy has been found to exhibit better performance against ball and armor piercing (AP) threats than 5083 but with

Bradley: Benefits of Various Aluminum Alloys

Experience with different aluminum alloys on the Bradley Fighting Vehicle has provided knowledge that can be applied to future vehicles.

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[25] This case study is based on W.B. Haworth, 1999, *The Bradley and How It Got That Way: Technology, Institutions, and the Problem of Mechanized Infantry in the United States Army*, Westport, Conn.: Greenwood Press; "Army Materials Research: Transforming Land Combat Through New Technologies," *AMPTIAC [Advanced Materials and Process Technology Information Analysis Center] Quarterly,* Vol. 8, No. 4, 2004, available at http://ammtiac.alionscience.com/pdf/AMPQ8_4.pdf; and NRI, http://www.army-technology.com/projects/bradley.

FIGURE 4-7 Bradley Fighting Vehicle. SOURCE: Available at http://osd.dtic.mil/photos/Nov2004/041030-F-2034C-040.html.

some loss in performance against fragmentation threats. However, 7039 has been found to be more susceptible to stress-corrosion cracking, especially in the short-transverse direction.

Combat survivability concerns were raised about the Bradley because it used aluminum armor, and ammunition is stored in the middle of the vehicle, but the Bradley has not experienced many losses. To improve survivability and armor protection designers added spaced laminate belts and high-hardness steel skirts to later versions. These additions increased overall weight by about 10 percent, to 33 tons, while decreasing the Bradley's mobility. Later versions of the Bradley and Abrams were designed to carry reactive armor[26] to protect against RPGs. This armor was employed in Iraq and proved effective in increasing survivability. In 2009, the Army awarded a contract to add armor to protect against improvised explosive devices (IEDs), as well as other enhancements of warrior protection.

4.5.4 Crusader 155mm Self-Propelled Howitzer[27]

The Crusader 155mm artillery system (shown in Figure 4-8) was intended to be the Army's next- generation self-propelled (SP) howitzer, replacing the M109A6 Paladin SP Howitzer and the M992 Field Artillery Ammunition Support Vehicle. It was initiated in 1994 to provide enhanced survivability, lethality, and mobility and therefore be more readily deployable than the platforms it replaced. In 2000, after a 60-ton developmental platform was produced, the Army restructured the program to meet the new weight requirement of 40 tons. This lower weight would allow two vehicles to be transported into theater on a C-5 or C-17 aircraft, reflecting the Army's planned transformation to a lighter, more deployable future force. The schedule called for DoD to decide in April 2003 whether the Crusader should enter development and demonstration; assuming they continued the program, production of an anticipated 1,100+ vehicles (later reduced to 480) was to begin in 2008.

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[26] From Jargon Database.com: "Reactive armor involves explosive devices attached to armored vehicles that explode before an incoming projectile strikes the vehicle. The ensuing outward explosion deflects or minimizes the inward momentum of the oncoming projectile." Available at http://www.jargondatabase.com/Category/Military/Army-Jargon/Reactive-Armor.

[27] This section draws on Government Accountability Office, 2002, "Defense Acquisitions: Steps to Improve the Crusader Program's Investment Decisions, February, available at http://www.gao.gov/new.items/d02201.pdf; and GAO, 2001, "Defense Acquisitions: Army Transformation Faces Weapon Systems Challenges, May, available at http://www.gao.gov/new.items/d01311.pdf.

FIGURE 4-8 Crusader 155mm self-propelled howitzer. SOURCE: Available at http://www.pica.army.mil/voice2002/020517/4_11_00%20Zone%206-1.jpg.

Crusader: Importance of a Broad Set of Goals for Lightweighting

Lightweighting primarily for transportability proved not to be a compelling reason to continue building a new system that was not sufficiently more capable than its upgraded predecessor—nor sufficiently ahead of its planned successor. Changing requirements, as a result of the end of the Cold War, added to costs and schedule.

In May 2002, Secretary Rumsfeld cancelled the $11 billion dollar Crusader program because it was deemed neither mobile enough nor precise enough. A GAO report determined that the improvement in transportability was not significant—two complete systems with supporting equipment would need four flights instead of five. More importantly, that report found that the majority of critical technologies were not sufficiently mature and that the Crusader's schedule had considerable overlap with the Future Combat System (see Section 4.5.5), which was intended to replace it. With upgrades, the existing fielded Paladin possessed sufficiently advanced performance characteristics to make it still an effective weapon in the land-based vehicle category to meet Army needs.

In the context of the lightweighting focus of this report, the desired C-17 transportability featured significantly in the design requirements central to the 155mm Crusader but did not take into account the transport of the supporting equipment. A 20 percent reduction in C-17 flights was not sufficient to make up for the immaturity of critical technologies and the rising costs.

4.5.5 Future Combat System (FCS) Combat Vehicles[28]

The Future Combat Systems (FCS) program was remarkably ambitious: a family of 14 high-tech manned and unmanned combat vehicles, encompassing robots and an array of sensors, connected in a single battle command-

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[28] This section is based on Andrew Feickert and Nathan Jacob Lucas, 2009, Army Future Combat System (FCS) "SpinOuts" and Ground Combat Vehicle (GCV): Background and Issues for Congress, Congressional Research Service, November, available at http://www.fas.org/

and-control network, at a cost of $92 billion (later increased to $164 billion). The Manned Ground Vehicle component was planned to provide eight FCS variants: an infantry carrier, a command-and-control vehicle, a mounted combat system, a reconnaissance and surveillance version, a non-line-of-sight cannon, a non-line-of-sight mortar, a recovery and maintenance vehicle, and a medical treatment variant.

FCS: Too Ambitious for Available Technology

The Future Combat System was a complex program with ambitious goals, including a lightweighting goal of building a combat vehicle with only one- quarter of the weight of the Abrams tank but similar speed and survivability. These goals depended on several technologies that required much additional development before they could be inserted in the combat vehicles. When development did not occur quickly enough for the FCS schedules, there were cost increases and delays.

The FCS was introduced in 1999 as the major research, development, and acquisition program intended to lead to the Army's transformation. Key requirements were C-130 transportability and an associated fully loaded weight of 30 tons. It was to be as durable and to offer as much protection as an Abrams Battle Tank, at only 25 percent of the weight. The weight requirement to allow C-130 transportability was considered crucial for landing in remote areas with, at best, primitive runways.

The drive to lightweighting of the FCS concepts included an effort to significantly lower fuel costs, which entailed a radical change in technology. Instead of a gas-diesel powered engines, as used in the Prius, the FCS called for development of the much less mature technology for diesel-electric hybrid engines. Another of the lightweighting strategies was to use new technologies for "active" defensive systems that have the capability to shoot down incoming threats such as RPGs, thus needing less heavy armor than the Abrams, which focuses on frontal attack survivability.

The Army treated its weight requirements as firm throughout much of the early tenure of the FCS program. Thus, when the concepts submitted by the two prime contractors for the main vehicle were overweight, the Army considered stripping some components to transport on a second aircraft, requiring additional logistical support to reassemble the vehicle in theater. However, in 2005 the Army removed the C-130 transportability requirement and substituted the stipulation that three FCS vehicles must fit in a C-17 heavy lift transport aircraft, thereby allowing the FCS vehicle weight to increase from 18 to 25 tons.[29]

During 2003-2009, the program underwent several rounds of restructuring. In April 2009, Secretary Gates recommended cancellation of the FCS Manned Ground Vehicle program. Secretary Gates and other critics gave several reasons for the demise of the FCS program, included its high cost and declining relevance for expected future defense needs. A chief listed cause is the reliance of FCS on technologies not yet mature; i.e., the technology readiness levels (TRLs) were too low, particularly for the high-tech "active" protection systems. In 2006, the GAO found that "none of FCS's 49 critical technologies was at a level of maturity recommended by DoD policy at the start of a program."[30] In 2008, GAO described the FCS as "about halfway through its development phase, yet it is, in many respects, a program closer to the beginning of development."[31] It was the need to bring a large number of needed technologies to maturity that led to cost increases, delays, and ultimately cancellation.

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sgp/crs/weapons/RL32888.pdf; Sandra I. Erwin, 2009, "Uphill Battle: Army's Next Combat Vehicle: New Beginning or FCS Sequel?," *National Defense*, August 1, available at http://www.highbeam.com/doc/1G1-205905726.html; Sandra I. Erwin, 2005, "Army Struggles with Weight of Future Combat Systems," *National Defense*, April, available at http://www.nationaldefensemagazine.org/archive/2005/April/Pages/UF-Army_Struggles5799.aspx; Sandra I. Irwin, 2005, "For Army's Future Combat Vehicles, Flying by C-130 No Longer Required," *National Defense*, November, available at http://www.nationaldefensemagazine.org/archive/2005/November/Pages/UF-For_Army5525.aspx.; and http://www.globalsecurity.org/military/systems/ground/fcs.htm.

[29] Sandra Erwin. 2005. "For Army's Future Combat Vehicles, Flying by C-130 No Longer Required." *National Defense.* November.

[30] GAO. 2006. "Defense Acquisitions: Improved Business Case Is Needed for Future Combat System's Successful Outcome." GAO-06-367. Available at http://www.gao.gov/new.items/d06367.pdf.

[31] GAO. 2008. "Defense Acquisitions: 2009 Review of Future Combat System Is Critical to Program's Direction, Statement of Paul L. Francis, Director Acquisition and Sourcing Management." GAO-08-638T. April. Available at http://www.gao.gov/new.items/d08638t.pdf.

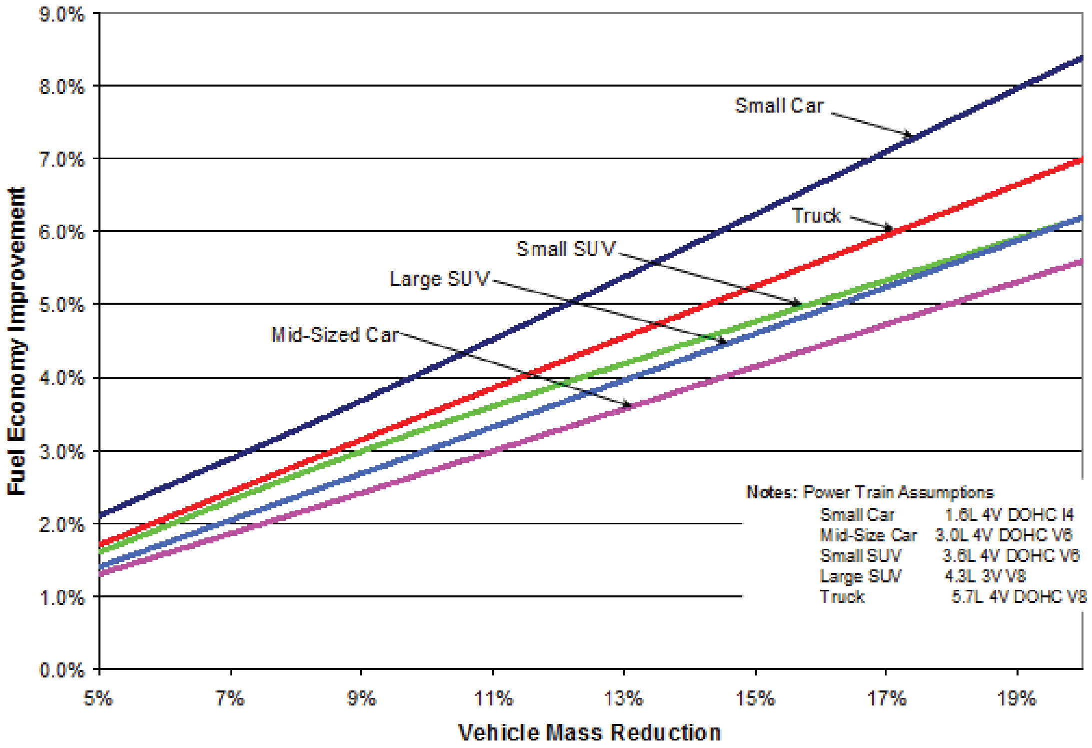

FIGURE 4-9 Impact of weight on fuel economy for personal vehicles. SOURCE: Bruno Barthelemy, Ford Motor Company, "Lightweight Technologies," presentation to the committee, October 2010.

4.5.6 Application of Systems Engineering to Lightweighting—Ford F-150 Example

Ford's customers rarely care about the weight of their vehicles per se, but they do care about the vehicle's purchase price, operating costs, gas mileage, durability, and performance. Lightweighting improves performance and gas mileage (Figure 4-9); the challenge is to obtain these benefits without sacrificing durability or crashworthiness. To achieve the best trade among performance, weight, cost, and gas mileage for the F-150 pickup, Ford uses a sophisticated systems engineering approach that involves a gated technology readiness assessment, a conceptual design that matches load lines to topology, and maximizes unitization to meet crashworthiness and durability requirements.[32]

Ford: Systems Engineering Supports Lightweightimg

It takes more than materials to achieve lightweight products. Systems engineering involves a broad group of experts so that materials, manufacturing, and assembly are all considered in the design of a system. A gated process makes sure that technologies are of sufficient maturity before they are used.

The systems engineering process brings together all elements that affect the design of the system—design, engineering, manufacturing, assembly, and materials specialists to define a concept to reduce weight without reducing crashworthiness or durability of the truck. The process is collaborative. Manufacturing brings its latest knowledge, experience, and scale-up demonstrations of hydroforming high-strength steels. Assembly brings its latest capabilities for laser welding and bonding. Together they bring their latest

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[32] Bruno Barthelemy, Ford Motor Company, "Lightweight Technologies," presentation to the committee, October 2010.

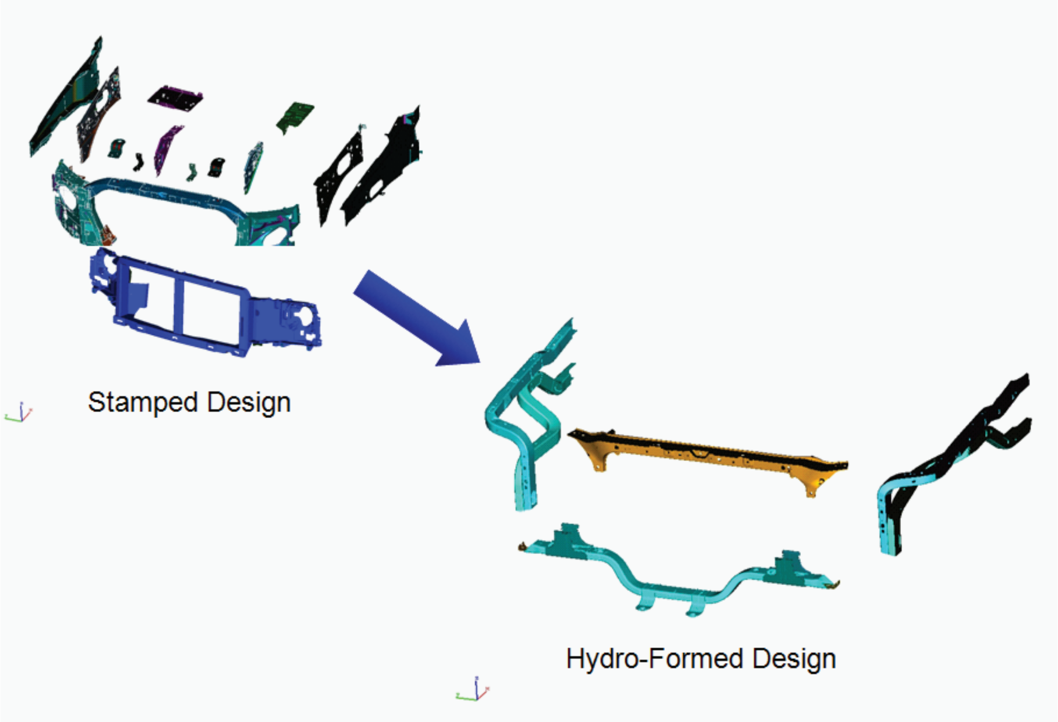

FIGURE 4-10 Improved topology offered by hydroformed substructures. SOURCE: Bruno Barthelemy, Ford Motor Company, “Lightweight Technologies,” presentation to the committee, October 2010.

demonstrations of combining hydroforming with simple laser welds to form parts with complex shapes. Materials specialists bring their most mature developments in high-strength steels since these offer thinner gauges for removing weight. The gated development process ensures that the technologies brought to the design trades have demonstrated scale-up and maturity required for application to the potential design.[33]

With these technologies on the table, the design team (including representatives from each technology area) can consider the forward cab section of the truck and reduce part count and simplify the design, as shown in Figure 4-10, while still meeting requirements for crashworthiness and durability. The simpler unitized design reduces welds significantly, thereby reducing cost and improving durability and stiffness. Moreover, the welds that are retained are designed to be easily applied with good access for the weld machines. In addition, the turns and twists permitted with the hydroformed substructures offer greater energy absorption for crash protection in the lighter weight structure.

All of the improvements noted above could have been achieved without significant advances in materials technology—assuming the steels were all hydroformable in the gauges required. The advanced high-strength steels offer smaller gauges to achieve higher-strengths and allow greater hydroformability as well. Consequently, the F-150 has seen a continuous improvement in weight reduction through advanced materials (Figure 4-11).

The topological design, afforded by the forming capability of the steels, provides a more modular assembly with fewer attach points, reducing assembly time and cost. The benefits to the customer are real, measurable, and result in a continuously improving product that is one of the most successful in its market.

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[33] Roy Williamson and Jon Beasley. 2011. “Automotive Technology and Manufacturing Readiness Levels.” Automotive Council of the UK, February. Available at http://www.automotivecouncil.co.uk/wp-content/uploads/2011/02/Automotive-Technology-and-Manufacturing-Readiness-Levels.pdf.

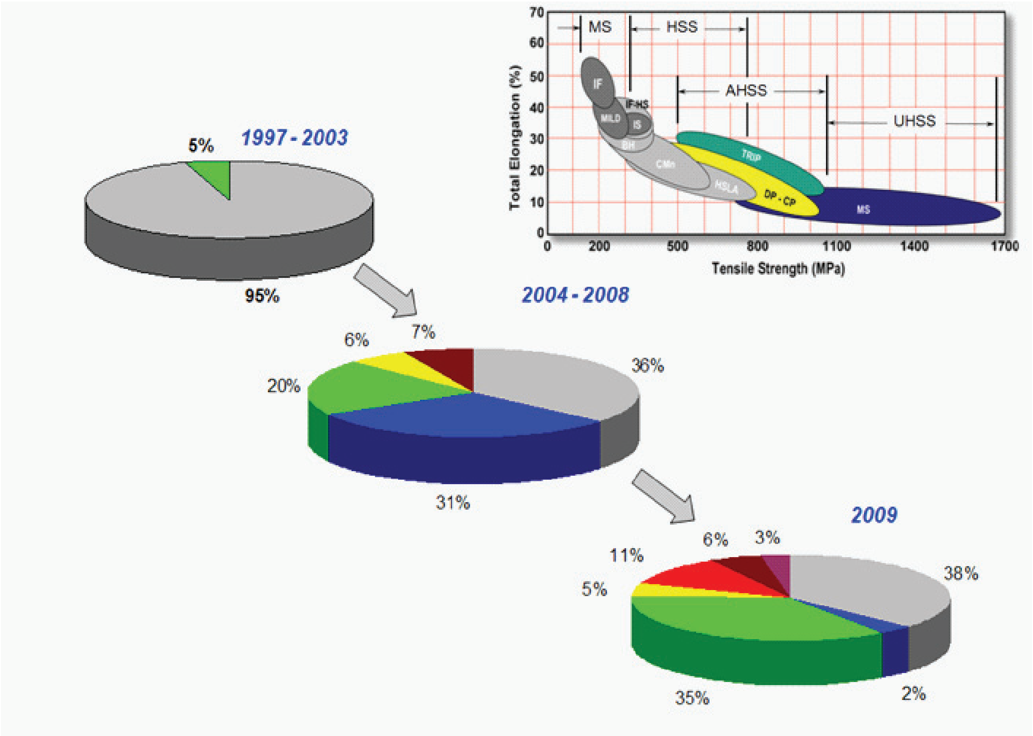

FIGURE 4-11 Continuous improvement in materials for the Ford F-150. MS, martensitic steel; HSS, high-strength steel; AHSS, advanced high-strength steel; UHSS, ultra high-strength steel. SOURCE: Bruno Barthelemy, Ford Motor Company, "Lightweight Technologies," presentation to the committee, October 2010.

4.6 CONCLUSIONS

- Lightweighting of land-based vehicles has been pursued as a means to facilitate air transport capability for rapid deployment, improve fuel economy, more readily cross open-water barriers, and enhance battlefield mobility and speed.
- Using aluminum alloys as primary hull materials for protection in tactical vehicles has proven effective in meeting many vehicle requirements, including speed, maneuverability, and survivability against some threats.
- Aluminum alloy hulls have not been able to provide the desired protection against the most lethal threats. The ever-increasing level of threat from RPGs, EFPs, shaped charges, mines, and IEDs has forced "up-armoring" across the various classes of land-based combat vehicles, with a concomitant increase in weight.
- Titanium and magnesium have properties that could greatly advance lightweighting, but there are many barriers to their utilization. Titanium is very expensive to extract. Magnesium is in short supply domestically and is also more expensive to form into useful product shapes than is aluminum or steel. Before either material can be widely used in lightweighting, new manufacturing technologies are needed to improve weldability, formability, spall resistance, fatigue resistance, and (particularly for titanium) susceptibility to corrosion in marine environments.
- The requirement for competitive prototyping (or, with a waiver, for a single prototype) prior to the engineering and manufacturing development phase can, in some instances, inhibit the use of new materials and new designs by not allowing adequate time for testing and validation.
- Because of the great emphasis on soldier protection as well as the pressures to control costs, lightweighting of land-based combat vehicles has proven to be more challenging than that of air and sea vehicles. Thus, it is not surprising that, apart from aluminum-based alloys, few new materials have found their way into extensive implementation in land-based vehicles.

5

Cross-cutting Issues and Challenges

This chapter expands on the key lightweighting topics introduced in Chapter 1 based on the discussion in that chapter and the assessments in Chapters 2-4.

5.1 DIFFERENT PRIORITIES, SIMILAR CHALLENGES

The preceding three chapters illustrate the point made in Chapter 1 and Table 1-1: that the key considerations that drive lightweighting differ markedly across vehicles for land, sea, and air transport. For instance, for ground vehicles, survivability is paramount to protecting the warfighter (see Chapter 4); performance attributes such as speed, maneuverability, and payload capacity are secondary. Furthermore, in today's combat environment, operational supportability related to fuel use and vehicle maintenance is viewed as less critical, although the vulnerability of logistics support is a concern. The priorities for naval ships differ. For example, design of the new class of littoral combat ship (LCS) is driven principally by performance (especially speed and maneuverability) and survivability (see Chapter 3). Operational supportability is generally secondary, although replacement of steels with aluminum alloys has implications for joining (see Box 5-1), fatigue, and repair. For aircraft, weight plays critical roles in both performance and operational supportability. It relates directly to propulsion and lift requirements, and hence to payload, range, speed, and fuel consumption. Survivability plays a secondary role overall, but a major role in the design of fighters and attack aircraft.

A summary assessment of lightweighting considerations for each medium—air, sea, and land—is given in Table 5-1. It illustrates that the use of metrics for design optimization relative to weight is most refined and mature for aircraft, and much less so for ground vehicles and maritime vessels. Future materials opportunities include high-strength steels, as well as more exotic materials such as titanium. As discussed in Chapter 2, composites are already used extensively in aircraft; they are also of interest for maritime applications.

Although the relative importance of lightweighting and attributes differs across the spectrum of military vehicles, lightweighting of all types of vehicles is hindered by at least two common barriers.

First, the time required to develop and certify new materials and process technologies generally exceeds that required for development and certification of a military vehicle. For example, it can take as long as 10 to 20

Box 5-1
Joining

The ability to join materials and structures together is fundamental to the construction of both military and civilian vehicles and their underlying structures, and perhaps presents the biggest challenge to the economical production of assembled multimaterial structures and complete vehicles while ensuring the complete integrity of the structures and vehicles. The challenge for doing this rapidly is becoming greater as new materials are introduced, requiring an expanded range of new joining techniques that are compatible with predominantly steel, aluminum, or composites vehicle chassis in military air, sea, or ground applications. Revolutionary improvements in joining can open new opportunities for weight and/or cost savings but need to be taken to the next level of advancement so that many promising technologies can be evaluated or confirmed and engineers can confidently specify their use. Joining techniques for major military body structure materials should be addressed in collaboration with the supply industry or through industry consortia.

There is a need for military manufacturers to evaluate and adopt adhesive bonding (which is growing in use in commercial automotive sectors) in combination with spot welding (known as weld bonding) or in combination with riveting (known as rivbonding). These technologies are being used increasingly for joining aluminum in some production situations, although it is generally necessary to have surface pretreatment to provide adhesive bond strength and durability.

A critical industry need exists to establish parameters and performance targets for assessing implementation readiness for such joining techniques as laser welding (e.g., continuous joining with reduced heat-affected zones), thermal drilling, and friction stir welding for assembling newer alloys of magnesium, aluminum, and advanced high-strength steel. The services need to work closely with manufacturers to define R&D projects involving real parts or performance conditions, in order to enhance the designers' confidence in these technologies.

Concurrent with joining technology developments, new non-destructive evaluation and inspection techniques are essential for developing manufacturing and assembly techniques and then for confirming the integrity of assemblies, vehicle structures, and systems in production. This is especially critical as lower-modulus materials are introduced and material thickness is reduced, thereby requiring that the integrity of the materials and joints consistently and economically meet the design targets for strength, stiffness, durability, and crashworthiness.

years to develop and implement a new advanced materials system.[1,2] Consequently, new materials and process technologies must be suitably mature at the time of preliminary design to ensure that the target vehicle will indeed be manufactured within the required timeframe; otherwise, sometimes-costly risk mitigation strategies must be implemented. Here, "maturity" encompasses the establishment of an adequate, stable supply of materials as well as the manufacturing capability to produce useful forms of these materials in order to ensure that the capability exists for streamlined insertion of lightweight materials into designs.

Second, the current acquisition process for military vehicles is expensive and lengthy.[3] Examples include the F-22 Raptor (19 years)[4] and the F-35B (9 years, although not a function of technical barriers).[5] The time and

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[1] Leo Christodolou, "Accelerated Insertion of Materials," DARPA presentation to the NRC committee on ICME, November 20, 2006, available at http://www7.nationalacademies.org/nmab/CICME_Mtg_Presentations.html.

[2] Materials Genome Initiative for Global Competitiveness, white paper and initiative prepared by the ad hoc Interagency Group on Advanced Materials, National Science and Technology Council, T. Kalil and C. Wadia, June 2011.

[3] See, for example, the NRC, 2011, *Evaluation of U.S. Air Force Preacquisition Technology Development*, Chapter 2, pp. 33-61, Washington, D.C.: The National Academies Press.

[4] Andrew McLaughlin. 2006. "F-22A Raptor—No Longer a Fair Fight," *Australian Aviation,* April, pp. 55-61. Available at http://www.ausairpower.net/AA-Raptor-0406.pdf. Last accessed June 21, 2011.

[5] Bill Sweetman. 2011. "F-35B Put on Probation; New Bomber to Go." *Aviation Week*, January 7.

TABLE 5-1 Summary Assessment of Lightweighting Considerations

	Summary Assessment		
General Considerations	Air (Transport and Tactical)	Sea (Non-nuclear Vessels)	Land (Tactical Vehicles)
Have explicit metrics been developed and used for weight optimization?	Yes—extensive and mature: • Component level • System level • Subsystems—engines, auxiliary power units, and so on	General, gross-level metrics: • Total weight • Weight distribution	General, gross-level metrics: • Total weight limits
Primary benefits of lightweighting	• Overall system performance—range, speed, payload, maneuverability • Support cost—fuel use	• Speed, maneuverability • Stability • Transportability	• Fuel use and associated logistics • Speed, maneuverability • Transportability
Primary challenges of lightweighting	• Cost and technical maturity of advanced materials	• Joining, structural health monitoring • Survivability and damage tolerance • Cost for mass volumes of lightweight materials	• Survivability—weight of armor • Advanced lightweight armor • Systems integration
Future materials opportunities (not including armor applications)	• Composite materials • Titanium	• High-strength steels • Aluminum • Composites	• Steels • Aluminum • Magnesium • Titanium

expense involved stem from extensive validation and certification requirements for new materials and processes as well as exhaustive testing of full-scale systems. Because the consequences of failure are severe, the principal decision makers tend to be risk-averse.

It is broadly recognized that the time to bring these technologies to fruition can be accelerated, and the prospects for attaining optimal designs enhanced, through the use of systems engineering design,[6] enabled by the unprecedented computational power at the disposal of the DoD. This approach also enables design for flexibility and adaptability. That is, since many legacy systems remain in service well beyond the initial targets of useful service life and often encounter new requirements or threats, new systems are ideally based on designs that allow modifications to be made when necessary after design and certification. Modifications can range from adding or replacing armor in land vehicles, as described in Chapter 4, to replacement of individual components as lighter (or otherwise improved) versions become available. The flexibility to accept such modifications would require consideration during the initial design of the vehicle external structure and the internals. Such flexibility could also result in improved maintainability as well as easier sustainment of legacy vehicles.

Specifically, the implementation and broader use of comprehensive materials models, as embodied by integrated computational materials engineering (ICME), need to be integrated with systems design and optimization

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[6] See, for example, NRC, *Pre-Milestone A and Early-Phase Systems Engineering*, pp. 1-13, Washington, D.C.: The National Academies Press. Also see reports and other resources available through the Defense Acquisition University website, at http://www.dau.mil.

analyses. This would ensure the consideration of potential new materials and enable analytic assessment of system benefits at an early stage of product development, as well as guide the selection and focus for new materials development. This is especially critical for lightweighting materials technology, because integration of the materials with design and configuration would be extremely important. The process could be further accelerated through greater use of advanced technology demonstration programs (see Chapter 1), which allow pursuit of technologies that have higher risk but the potential for higher pay-off.

A third common barrier is that there is limited availability of some materials critical to lightweighting, or the materials are prohibitively costly. Moreover, the specialized manufacturing capabilities needed to create some of these materials, or to form them into useful structural shapes, are, in some cases, in short supply.

5.2 SYSTEMS ENGINEERING DESIGN

5.2.1 Approaches and Trade Spaces

As discussed in Chapter 1, systems engineering design requires consideration of many (often conflicting) requirements for vehicle performance and functionality. It is broadly recognized as being essential to optimization over the system trade space (which defines how changes in one aspect of a system, such as in the type and amount of a material used, or the structural form of a component, affect all other aspects), based on the interrelationships among material technology, structural forms, and performance (as well as costs). The task can be extraordinarily complex.

Optimization[7] of a military vehicle requires clear definitions of the performance metrics—top speed, range, survivability under prescribed threats, and operating costs being common examples—as well as the weighting of these metrics (to establish their importance relative to one another). The optimization process thus requires understanding of the operational trade space: that is, how changes in one aspect of a system—the type and amount of material used in a component or its structural form—affect all relevant performance indices. In some cases, multiple benefits can accrue. Lightweighting, for example, can lead to increased fuel efficiency (assuming no change in functional requirements), increased vehicle range, and increased payload capacity. It can also be used to enhance survivability by use of additional armor without necessarily changing the overall vehicle weight. However, these changes can also be accompanied by increased acquisition costs, which can take precedence over life-cycle costs in procurement.

Although the systems engineering approach has been successful in recent military vehicle projects, a number of barriers prevent it from taking full advantage of the potential for lightweighting to improve system attributes:

- As discussed earlier in this chapter and throughout the report, the timeline for materials development exceeds the timeline for product development, preventing or significantly delaying the incorporation of new materials.
- Material development and optimization have not been an explicit part of the system optimization process.[8] The biggest impediments to this are the time, cost, and risk of material development and certification.[9] Consequently, optimization can be performed only over the domain of certified materials.

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[7] "Optimization" is certainly the ideal goal of systems engineering, but practitioners recognize that, in complex military systems, which typically have hundreds of requirements and numerous subsystems, optimization in the truest mathematical sense is not feasible due to difficulties in defining clear objective functions across the many interacting constraints. In this context, the committee uses the word "optimization" to mean state-of-the-art optimization strategies to design best possible system using realistic constraints.

[8] Michael Winter, P&W, "Infrastructure, Processes, Implementation and Utilization of Computational Tools in the Design Process," presentation to the NRC committee on ICME, March 13, 2007, available at http://www7.nationalacademies.org/nmab/CICME_Mtg_Presentations.html.

[9] See, for example, G.L. Hahn et al., "Accelerated Insertion of Materials—Composites," presentation, 34th SAMPE Conference, 2002; and Z. Lui, P. Witte, J. Ceisel, and D.N. Mavris, "An Approach to Infuse Manufacturing Considerations into Aircraft Structural Design," 56th SAMPE Conference, May 2011.

- The current military procurement and acquisition process, whereby portions of vehicle systems are subcontracted to different vendors, can lead to sub-optimization at the subcontract level, or even to development of non-optimized subsystems, if systems engineering processes are not adequately followed or enforced.
- Explicit performance metrics and their weightings are ill-defined, especially in ground vehicles.
- The computational design tools used today for systems engineering and optimization by the DoD and original equipment manufacturers (OEMs) do not generally include comparable analytical materials design and behavior models. Development and integration of such comprehensive materials models (ICME) with other systems analysis tools offers the potential to accelerate prototyping (especially preacquisition phase prototyping) as well as make it possible to conduct rapid studies of the trade space. Such tools would also result in better selection and evaluation of the most critical lightweighting materials technologies for future investment.

The implementation and broader use of comprehensive materials models, as embodied by ICME, would have to be integrated with systems design and optimization analyses. This approach would ensure the consideration of potential new materials and enable analytical assessment of system benefits at an early stage of product development, as well as guide the selection and focus for new materials development. This is especially critical for lightweighting materials technology, since integration of the materials with design and configuration would be extremely important.

5.2.2 Integrating ICME into Systems-Level Design and Optimization

As noted in Chapter 1, the statement of task encompasses the design of components, structures, and vehicles. This goes beyond the use of lightweight or otherwise advanced materials, extending to how materials are arranged and topologies optimized. Many of the innovations in lightweight construction are concerned with putting the material where it is most beneficial. Advances in system design and topology can yield improvement in performance even absent the incorporation of new materials.

Hardware design is an iterative process that starts with a set of specifications and functional requirements from which a designer must develop a conceptual design establishing the overall form of the hardware to be designed. The conceptual design needs to be optimized to best satisfy the specifications and functional requirements. Then the design must trade off structural concepts and topologies, materials, manufacturability, service environments, and so on.

Structural topology is an important area of research and is an integral element of the systems-level design approach discussed in this report. An example of the approach can be found in, “Materials Selection Combined with Optimal Structural Design: Concept and Some Results.”[10] In this article the authors link materials data from the Cambridge Material Selector (CMS) with a design optimizer (the Multipoint Approximation method with Response Surface fitting, or MARS) to produce a final design for an automobile structural component. Figure 1 of the article, shown here as Figure 5-1, illustrates the approach.

In this approach, material and performance indices are derived on the basis of performance targets, standards and other regulatory requirements, and load analyses. The authors used the CES for preliminary material selection. To optimize the structure of the component, the authors developed a system based on MARS combined with MSC.MARC FEA code w9x.[11] Because the material selection was considered as a multiobjective optimization, a compound objection function was used as shown at the bottom of Figure 5-1. The final choice of material can then be made on the basis of minimization or maximization of the compound objective function, depending on the problem to be solved.[12]

Fundamental advances in structural topology are being made in both the United States and Europe that could

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[10] N.S. Ermolzeva, K.G. Kaveline, and J.L. Spoormaker. 2002. “Materials Selection Combined with Optimal Structural Design: Concept and Some Results.” *Materials and Design,* Vol. 23, Issue 5, August, pp. 459-470.

[11] Ibid.

[12] Ibid.

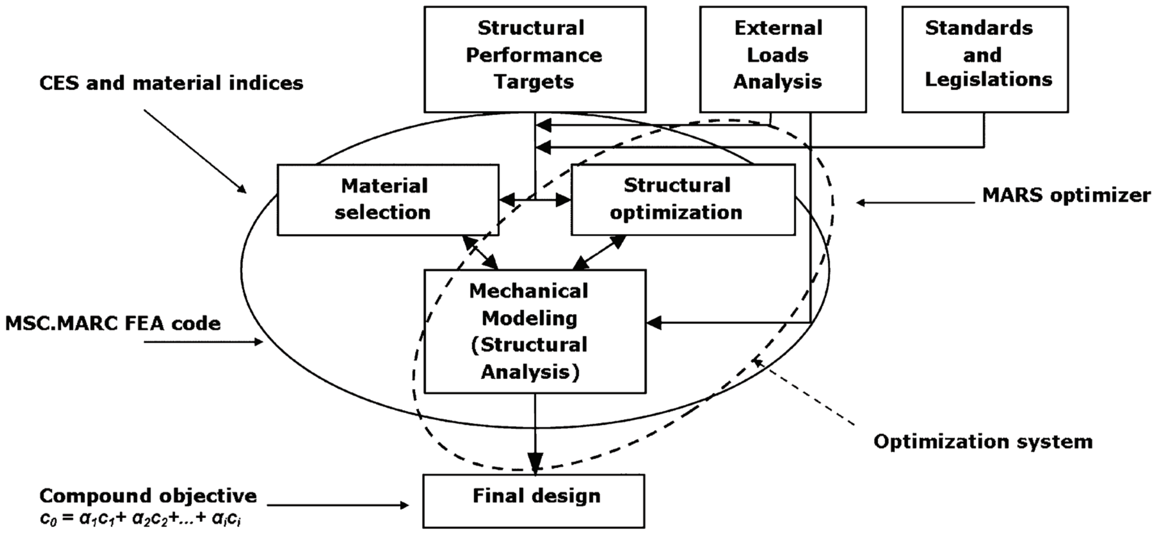

FIGURE 5-1 An approach to combining materials selection with structural optimization. SOURCE: N.S. Ermolzeva, K.G. Kaveline, and J.L. Spoormaker. 2002. "Materials Selection Combined with Optimal Structural Design: Concept and Some Results." *Materials and Design,* Vol. 23, Issue 5, pp. 459-470.

contribute greatly to the lightweighting of military and civilian vehicles. An example is the work at Johns Hopkins University on topology optimization, a computational method for optimizing the design of structural systems as well as the design of multifunctional materials.[13] Recent work at the University of Notre Dame has investigated structural topology optimization for blast mitigation in ground vehicles.[14] These tools and techniques are being used in the private sector,[15] but the technology is still a long way from being fully developed.

Accelerating the development of improved analytical tools for doing structural topology optimization would improve the speed and fidelity of the conceptual design phase. This research needs to be fully integrated into the overall systems-level analyses for efficient development of lightweighting solutions.

5.2.3 Design for Flexibility and Adaptability

Because the functional requirements placed on military vehicles may change over their service lives, adaptability and flexibility are important considerations when the vehicles are designed. However, designing for flexibility can lead to bloated systems as more features and capabilities are added. Indeed, in some sense, designing for flexibility is the antithesis of lightweighting. Additionally, flexibility often means compromising the performance goals for any one specific application. An example of this dilemma is the Joint Strike Fighter (F-35): it was designed to suit all of the services and, as a result, is heavier than originally desired.[16]

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[13] See, for example, J.K. Guest and J.H. Prévost, 2006, "Optimizing Multifunctional Materials: Design of Microstructures for Maximized Stiffness and Fluid Permeability," *International Journal of Solids and Structures,* Vol. 43, Issues 22-23, November, pp. 7028-7047; A. Asadpoure, M. Tootkaboni, and J.K. Guest, 2011, "Robust Topology Optimization of Structures with Uncertainties in Stiffness—Application to Truss Structures," *Computers & Structures,* Vol. 89, Issues 11-12, June, pp. 1131-1141; and E. Lund, 2009, "Buckling Topology Optimization of Laminated Multi-material Composite Shell Structures," *Composite Structures,* Vol. 91, Issue 2, November, pp. 158-167.

[14] J.C. Goetz, H. Tan, J.E. Renaud, and A. Tovar. 2009. "Structural Topology Optimization for Blast Mitigation Using Hybrid Cellular Automata." *Proceedings of the 2009 Ground Vehicle Systems Engineering and Technology Symposium.* August 28-20, Troy, Mich.

[15] See, for example, "Study of Topography Optimization on Automotive Body Structure," presentation by Rajan R. Chakravarty, General Motors, at the SAE World Congress & Exhibition, Detroit, Mich., April 2009.

[16] In 2004, it became apparent that the STOVL (Short Take-Off Vertical Landing) variant of the Joint Strike Fighter was exceeding its weight targets to such an extent that it might be unable to accomplish its mission. A team was assembled to find ways to reduce its weight, which was done primarily by reducing its mission requirements. For example, an original design specification to carry two internal air-to-ground weapons in the 2000-pound class was changed to two weapons in the 1000-pound class, providing a 2000-pound weight reduction. See E.L.

A concept of flexibility embraced by the services is that of "multifunction structure plus," wherein structural components perform additional functions. Examples include the Army's use of structural batteries embedded within armor systems,[17] the Navy's advanced enclosed mast system (see Chapter 3), and the Air Force's use of composites for both damage resistance and electromagnetic environment protection (see Chapter 2). Another area that aircraft manufacturers are considering involves lightning strike protection. Currently, because of the poor electrical conductivity of the polymer resins used in the composites, conducting metallic meshes must be added. Emerging technologies to embed carbon nanoparticles in the resin may raise the conductivities to the requisite levels and obviate the need for the mesh material in advanced composites. This could also yield additional benefits in the out-of-plane stiffness and strength.[18]

5.3 INSERTION OF LIGHTWEIGHTING MATERIALS AND TECHNOLOGIES

5.3.1 Timeline for Technology Development and Insertion

As discussed in Chapter 1, the time required to develop and certify materials generally exceeds that required for product development and certification. The time can range widely—from a few years for derivative materials on an expedited schedule to a decade or longer when a new class of material is under development or where new infrastructure is required to produce the material or structure.[19] The major challenge is to shorten the timeline for materials development and bring it in line with that for product development.

This challenge is made more difficult by the mandates of the rigorous, gated[20] approaches taken for development and certification of major engineering systems, which require that the maturity of new technologies be relatively high by the time critical system architecture decisions are made—typically when detailed design is initiated. New technologies that are not sufficiently mature at this stage are excluded from consideration unless backup configurations are carried along for risk mitigation. Unacceptably high levels of risk could be incurred if system architecture, design, or capability is critically dependent on a new technology, and failure to bring that technology to fruition results in significant design changes, compromises to system attributes, or delays in production.

Many companies and DoD agencies use the technology readiness level (TRL) assessment process, and the corresponding manufacturing readiness level (MRL) scale, for assessing and describing the maturity of materials and processing technology and the readiness of the corresponding manufacturing technologies and processes. The TRL scale and its definitions of maturity levels—originally proposed for use by NASA in the late 1980s and detailed in the *Defense Acquisition Guidebook*[21]—are summarized in Table 5-2. Definitions for the corresponding MRLs, which were developed and aligned with the TRL definitions somewhat later, are also shown. The TRL and corresponding MRL gate definitions are very consistent in scope and intent. In fact, through TRL-7 and MRL-7, the MRL gate exit criteria require that the corresponding TRL gate criteria be met as a condition of MRL gate completion.

When the TRL assessment approach is applied to materials and process development, the timeline and typical decision gates appear as illustrated in Figure 5-2. Two gates are often critical: TRL-3 (and MRL-3), where deci-

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Palmer, 2008, "F-35 Lightning II News: Weighing the F-35," *F-16.net,* March 16, available at http://www.f-16.net/news_article2784.html. Last accessed May 26, 2011.

[17] *AMPTIAC Quarterly,* Vol. 8, No. 4, 2004.

[18] See for example, (1) B. Wang, R. Liang, C. Zhang, P. Funches, and L. Kramer, 2003-2004, "Investigation of Lightning and EMI Shielding Properties of SWNT Buckypaper Nanocomposite," Final Report, May 1, 2003-October 31, 2004, available at http://handle.dtic.mil/100.2/ADA430333'; (2) T.W. Chou, L. Gao, E.T. Thostenson, Z. Zhang, and J-H Byun, 2010, "Review: An Assessment of the Science and Technology of Carbon Nanotube-based Fibers and Composites," *Composites Science and Technology,* Vol. 70, No.1, January, pp. 1-10; and (3) K. Kalaitzidou, H. Fukushima, and L. Drzal, 2010, "A Route for Polymer Nanocomposites with Engineered Electrical Conductivity and Percolation Threshold," *Materials*, Vol. 3, pp. 1089-1103, available at http://www.mdpi.com/1996-1944/3/2/1089.

[19] NRC. 2004. *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=11108.

[20] Gated technology developments programs specify criteria that must be met before a project can advance through a "gate" from one development stage to the next.

[21] *Defense Acquisition Guidebook,* available at https://akss.dau.mil/dag/DoD5000.asp?view=document&rf=GuideBook\IG_c10.5.2.asp.

TABLE 5-2 Technology and Manufacturing Readiness Levels and Maturity Descriptions

	TRL or MRL Level	TRL Maturity Description	MRL Maturity Description
Pre-Acquisition Technology Development Phase	1	Basic principles observed and reported	Basic Manufacturing Implications Identified
	2	Technology concept and/or application formulated	Manufacturing Concepts Identified
	3	Analytical and experimental critical function and/or characteristic proof of concept	Manufacturing Proof of Concept Developed
	4	Component and/or breadboard validation in laboratory environment	Capability to produce the technology in a laboratory environment
	5	Component and/or breadboard validation in relevant environment	Capability to produce prototype components in a production relevant environment
	6	System/subsystem model or prototype demonstration in a relevant environment	Capability to produce a prototype system or subsystem in a production relevant environment
Acquisition Phase	7	System prototype demonstration in an operational environment	Capability to produce systems, subsystems, or components in a production representative environment
	8	Actual system completed and qualified through test and demonstration	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production
	9	Actual system proven through successful mission operations	Low rate production demonstrated; Capability in place to begin Full Rate Production
	10	Not defined	Full Rate Production demonstrated and lean production practices in place

SOURCE: Defense Acquisition Guidebook and DoD/MRL Manufacturing Readiness Level (MRL) Deskbook, version 2.0, May 2011.

sions to invest in comprehensive development and validation occur, and TRL-6 (and MRL-6), where materials, processes, and manufacturing readiness are considered sufficiently mature for use. This level of maturity is usually required for a technology to be included in the detailed design phase of a product or system.

For major DoD systems, development and acquisitions must adhere to Defense Acquisition Management System requirements. Three key milestones defined in this process relate to technology introduction. These milestones, illustrated in Figure 5-3, are defined by DoDI 5000.02:

1. *Milestone A:* approval of entry into the Technology Development (TD) phase;
2. *Milestone B:* approval of entry into the Engineering and Manufacturing Development (EMD) phase; and
3. *Milestone C:* approval of entry into the Production and Deployment (P&D) phase.

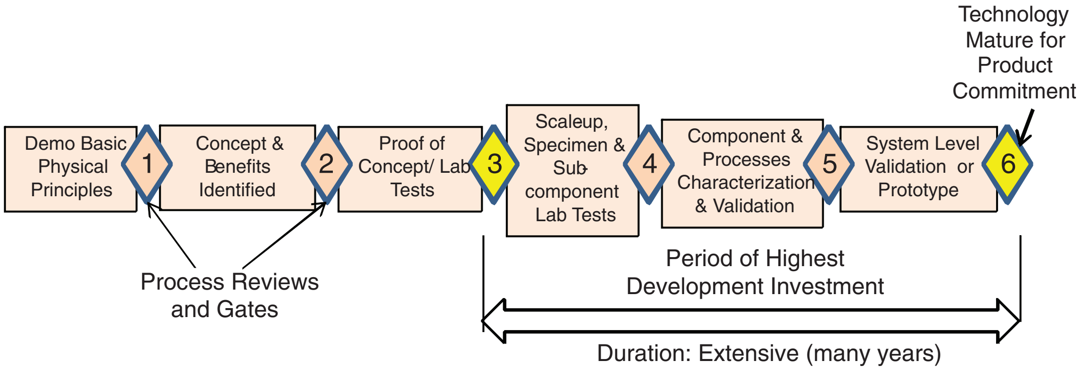

FIGURE 5-2 Typical technology readiness level (TRL) gates for development of materials and processes. The time period may vary widely, from around 2 years for derivative materials to >5 years for critical structural materials or when significant new materials systems or infrastructure are associated with the technology. Gate 3 is typically where significant investment and specific application focus begin. TRL-6 and MRL-6 are usually required prior to program initiation or product commitment. SOURCE: Adapted from B.A. Cowles and D. Backman, 2010, "Advancement and Implementation of Integrated Computational Materials Engineering (ICME) for Aerospace Applications," a white paper sponsored by the Air Force Research Laboratory, AFRL-RX-WP-TP-2010-4151, March, available at http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA529049.

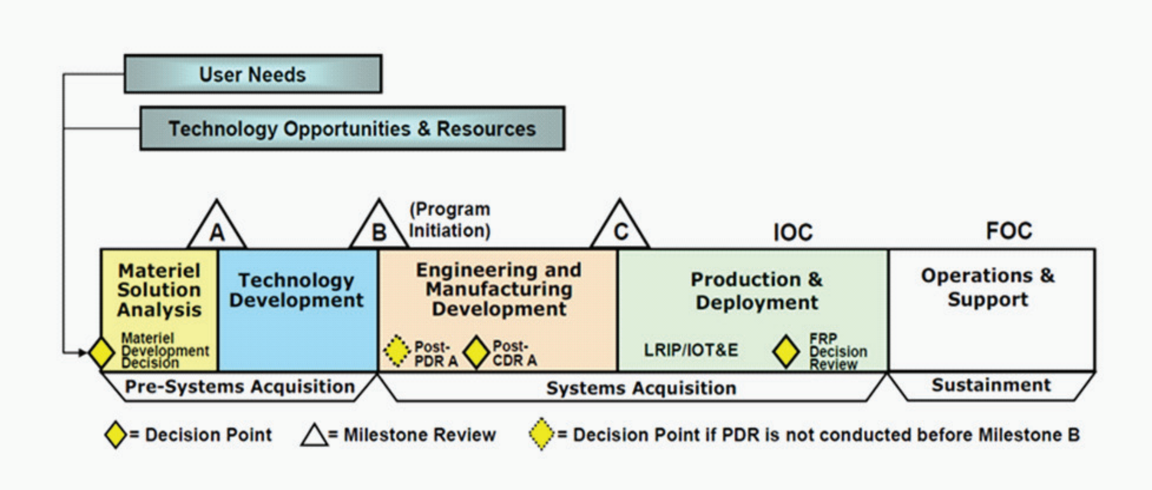

FIGURE 5-3 Defense acquisition system-level milestones. SOURCE: Department of Defense, *Defense Acquistion Guidebook,* Instruction 5000.02, December 8, 2008.

Perhaps the most important considerations regarding the relationship between technology readiness and these key system-level milestones are these:

- Technology and manufacturing maturity levels are required to be at TRL-6 and MRL-6, respectively, at or before Milestone B, when engineering and manufacturing development for the product or system begins.
- The Technology Development phase, which begins at Milestone A, must have sufficient scope, resources, and time to mature candidate technologies to TRL-6/MRL-6 before program initiation at Milestone B.

The implications of this requirement are significant. If the time, cost, or risk of maturing a new materials or processing technology prevents achievement of TRL-6, and/or MRL-6, by the time of program initiation at Milestone B, then it is likely that the technology will not be included in the system development. If it is included, some level of risk mitigation activity will be required. Risk mitigation activities may be significant depending on the impact the technology is expected to have on the system architecture, design, or capability.

The Technology Development phase is critical for both selection and maturation of technologies. This is especially true for lightweighting materials and related technologies, since—as described in this report—taking full advantage of lightweighting requires integration of such materials and technologies at the system level. This requires consideration of technologies and their potential impact well before Milestone B, and a commitment for their development and maturation before the detailed design phase and program initiation. An excellent discussion of the need for strategic selection of technologies, and this recurring issue of "bridging the valley of death" for technology insertion, can be found in the recent NRC report *Evaluation of U.S. Air Force Preacquisition Technology Development*[22] (discussed in Chapter 1 of this report).

A generic representation of a gated product or system development process is shown in Figure 5-4. This expands the first part of the DoD graphic in Figure 5-3 slightly, in order to better illustrate the activities that occur from Milestone A (preacquisition technology development) into the acquisition phase where Milestones B and C occur.

The alignment of technology and manufacturing development with the product or systems development process is illustrated in Figure 5-5. Although the timelines for specific technologies and the programs themselves may vary widely, it is apparent that accelerating the materials and processes development cycle is critical. Technologies not already at TRL-3 (MRL-3) would likely have a difficult time being considered, even in the concept optimization phase. Moreover, higher levels of maturity would be expected or required before commitment of a materials technology to preliminary design activities. For technologies and design approaches with significant implications for system integration, such as materials and processes for lightweighting, benefits and impacts would best be assessed during the concept initiation phase—very early in the product development process, and early in the Technology Development phase of the Defense Acquisition process.

Ideally, technology development and product or system development would be interactive from inception of both phases. In such an ideal state, product concepts would influence technology (including materials) developments, beginning at the conceptual (and low- maturity) stage, and analysis of potential materials and their capabilities would be passed back to the concept initiation activities for product development. This loop would be iterated and refined to guide both product and materials/technology development—including the selection of appropriate technologies for investment. This is illustrated in Figure 5-6.

Then, again ideally, an accelerated materials and processes development and certification process would begin, in time to meet requisite maturity levels by the start of Program Initiation, corresponding to Milestone B and detailed design. Future materials and process technologies will require reductions in the time, cost, and risk of development and certification. Regardless of whether such an idealized process could be supported in practice, it is clear that accelerating the design, development, and insertion of new materials and manufacturing processes is critical to future products and systems. This is especially true for lightweighting materials technologies, which would be best selected and assessed as part of an integrated systems development process.

The next section discusses some approaches to better integrating the development of materials technologies with development of entire systems. The committee believes that ICME offers significant potential to enable improved materials design, accelerated development, and reduced risk for insertion. In addition, the capability to analytically describe materials in a manner compatible with processes for design and concept optimization will be essential to having these materials considered and integrated at the earliest stages of product development.

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[22] NRC. 2011. *Evaluation of U.S. Air Force Preacquisition Technology Development*. Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog/13030.html.

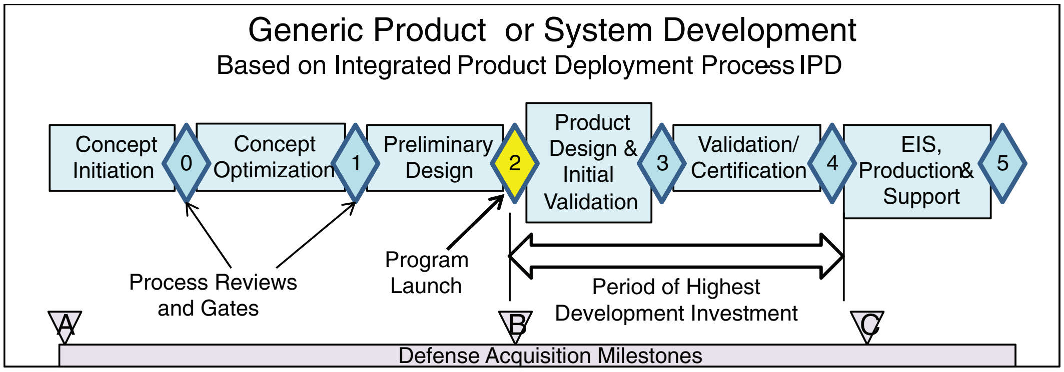

FIGURE 5-4 Generic gated product or system development process. Gate 2 is a key gate: it corresponds to defense acquisition process Milestone B, program initiation, where TRL-6 and MRL-6 maturity levels are required. The time to advance from gate 2 to gate 4 can vary widely: from perhaps 2 years for a derivative system to more than 10 years for a complex major system. SOURCE: Adapted from B.A. Cowles and D. Backman, 2010, "Advancement and Implementation of Integrated Computational Materials Engineering (ICME) for Aerospace Applications," a white paper sponsored by the Air Force Research Laboratory, AFRL-RX-WP-TP-2010-4151, March, available at http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA529049.

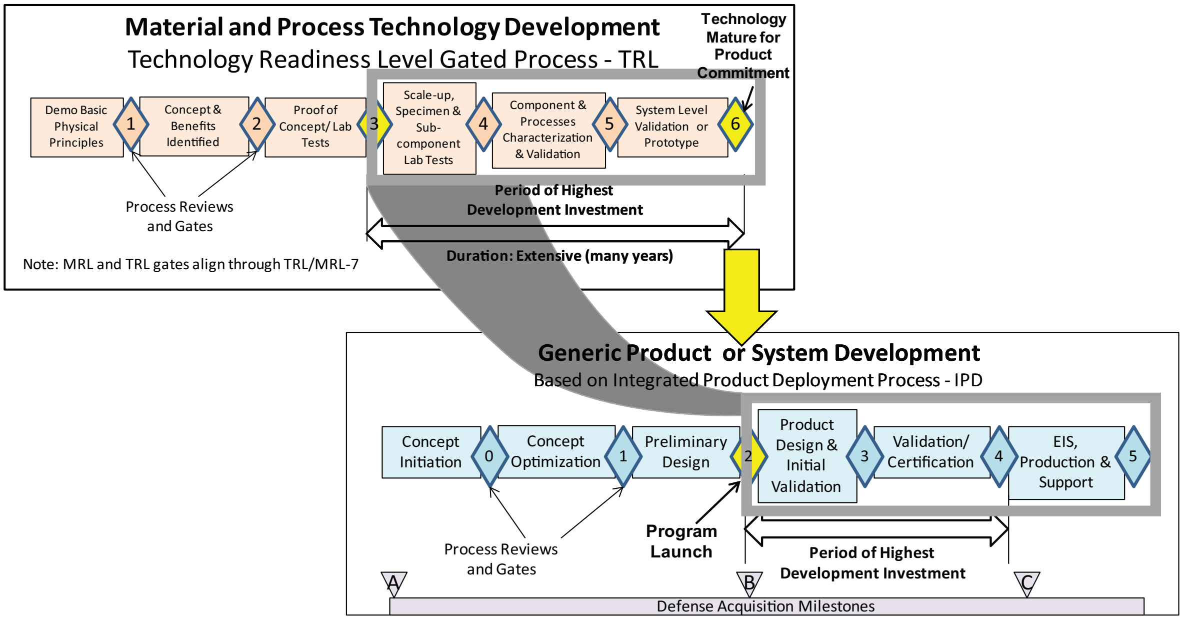

FIGURE 5-5 How technology readiness for materials and processes relates to product and system development. SOURCE: Adapted from B.A. Cowles and D. Backman, 2010, "Advancement and Implementation of Integrated Computational Materials Engineering (ICME) for Aerospace Applications," a white paper sponsored by the Air Force Research Laboratory, AFRL-RX-WP-TP-2010-4151, March, available at http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA529049.

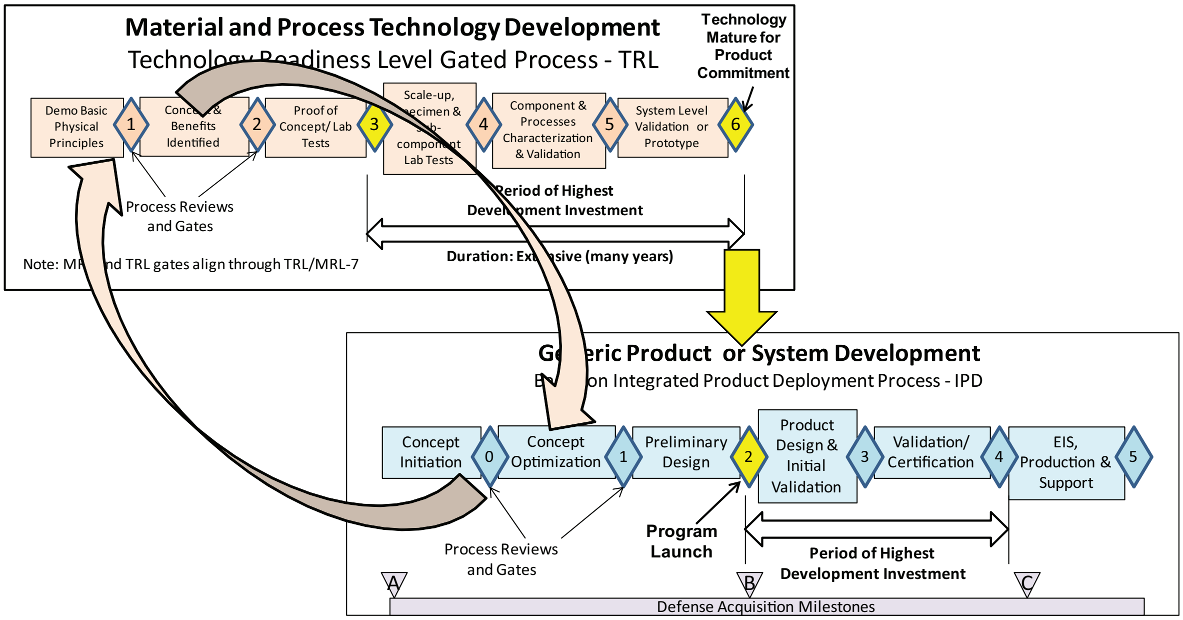

FIGURE 5-6 Ideal integration of early materials technology development and early systems development processes. SOURCE: Adapted from B.A. Cowles and D. Backman, 2010, "Advancement and Implementation of Integrated Computational Materials Engineering (ICME) for Aerospace Applications," a white paper sponsored by the Air Force Research Laboratory, AFRL-RX-WP-TP-2010-4151, March, available at http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA529049.

5.3.2 Enabling Engineering Tools: (i) ICME

In the context of materials and process develoment, integrated computational materials engineering is the analog to systems engineering in vehicle design. For ICME, the "system" is the set of manufacturing processes, materials systems, and engineering applications.

The primary potential of ICME is more efficient and robust engineering of products, manufacturing processes, and materials.[23] Improved efficiency can take the form of reduced development time, reduced certification time, or reduced development costs. ICME allows quantitative tradeoffs between material properties and manufacturing capabilities. It can lead to the development of new engineering products using existing materials, refinement of existing materials and manufacturing processes, or development of new materials and manufacturing processes. Two examples of successful ICME demonstrations are described in Boxes 5-2 and 5-3.

The example in Box 5-2 demonstrates the inherent advantage of computationally designed materials over empirically discovered materials in implementation of the accelerated insertion of materials (AIM) method, as the same tools and databases that are used to create the material also support the AIM models. These tools enable a "design for manufacturing" approach up front, eliminating scale up and streamlining qualification testing. ICME tools can be applied to the development of all vehicles, military and civilian. The use and further development of these tools for military purposes would be expected to benefit the development and improvement of commercial land, air, and maritime vehicles.

Figure 5-2-2 in Box 5-2 shows the iSIGHT-based Monte Carlo simulation of property variation in manufacturing (blue line), which used data from only three production-scale heats to accurately forecast 1 percent minimum

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[23] NRC. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12199.

design allowables. The model was validated by 10 production scale heats ("experimental data") where the final designed 1 percent allowable ultimate tensile strength (UTS) was within 1 ksi of the data (inside the red ellipse). This approach employed the linear-transformation sparse data fusion strategy first demonstrated for aeroturbine superalloys during DARPA-AIM. The forecast allowed fine-tuning of process optimization at an early stage, eliminating re-testing costs in the qualification cycle.[24]

5.3.3 Enabling Engineering Tools: (ii) Physics-Based Models of Material Behavior

Future military technologies will place increasing demands on materials in extreme service environments—notably, under high levels of stress, strain, strain rate, temperature, and heat flux. Tremendous progress has been made over the past two decades in the development of finite element codes for thermostructural analysis. Significant advances have also been made in the development of continuum-level constitutive laws for inelastic deformation, damage evolution, and rupture. Together, the finite element codes and the constitutive laws have proven effective in analyzing structural response over a wide range of loading conditions. Notwithstanding this progress, there remain large gaps in the understanding of the underlying physical processes that operate in complex multiphase systems, especially at very high strain rates and in the shock domain. New information-rich experiments and corresponding material models are needed. Specific areas that require attention include:

- The linkage of strength, damage evolution, and fracture to material chemistry, processing history, and microstructure;
- Techniques to bridge time and length scales in material models; and
- New numerical techniques to model the pertinent physical processes with high fidelity and exploit the computational power now available to the DoD.

The U.S. Department of Energy has sponsored extensive work in physics-based modeling and simulation at its national laboratories, much of it to support the Nuclear Test Ban treaty (i.e., to provide assessments of material and structural behavior for nuclear weapons in the absence of testing). The fundamental physics codes developed for this purpose are relevant for all materials design efforts. For example, work at Sandia National Laboratories has resulted in open-source tools for molecular modeling that has been used extensively and is continuously updated to add more fundamental physics information and to increase computational speed. Continued progress on such physics-based modeling and simulation is needed.[25]

Example of Modeling Challenges: Polymer Composites

An example of the progress and the disconnects in current modeling abilities for materials relevant to structural lightweighting is in the area of polymer composite materials. Composites consist of a polymer resin material of specific chemical structure, a fiber reinforcement, a surface modification of the fibers, and a defined geometric arrangement of the fibers within the matrix. Recently, nanoparticles have been added to the resin and/or the fiber/matrix interfaces, where the nanoparticles themselves typically possess a surface chemical functionalization to make them compatible with the matrix material. These composites are constructed through a variety of processing methods, during each of which variations in temperature, pressure, and other processing conditions significantly affect the final composition and properties of the composite material. Current chemistry models can address changes in the viscosity of resins due to alterations in the polymer backbone chemistry and molecular weight, and processing models can predict the flow of polymer through a fiber mesh to guide infiltration. In addition, macro-level relationship metrics between resin chemistry and toughness of resin have been developed. To tune stiffness and

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[24] C.J. Kuehmann and G.B. Olson. 2009."Computational Materials Design and Engineering." *Materials Science and Technology,* Vol. 25, Issue 4, pp. 472-478. Available at http://www.mendeley.com/research/computational-materials-design-engineering/.

[25] A survey of computational models for failure, damage, and degradation in composite materials can be found in Appendix E of NRC, 2005, *Going to Extremes: Meeting the Emerging Demand for Durable Polymer Matrix Composites*, Washington, D.C.: The National Academies Press, available at http://www.nap.edu/catalog.php?record_id=11424.

Box 5-2
ICME Example: Flying Cybersteel

An important milestone in ICME technology has been the streamlined flight qualification of the Ferrium S53 aircraft landing gear steel, the first fully computationally designed and qualified material. Using the multiscale systems approach represented by Figure 5-2-1, computational tools were used to apply predictive science to each of the process/structure, structure/property, and property/performance links indicated by connecting lines. Computational multicomponent thermodynamics[1] were used to combine materials science, applied mechanics, and quantum physics for parametric design integration.

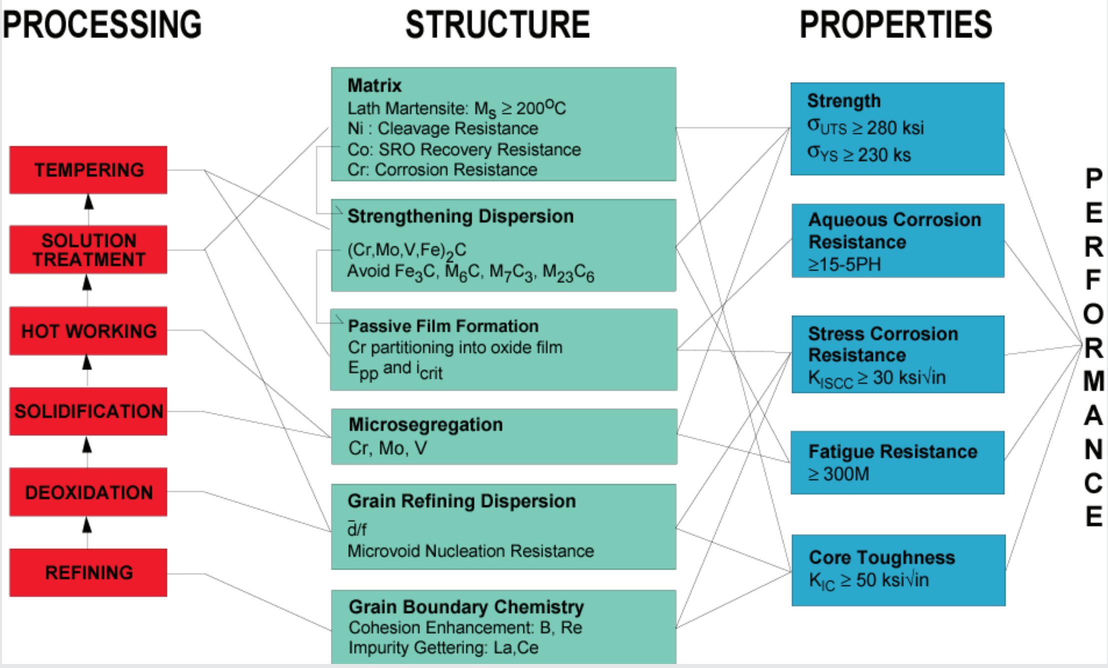

FIGURE 5-2-1 System chart representing Ferrium S53 landing-gear steel. SOURCE: G.B. Olson. 2011. "Computational Materials Design: Making CyberSteel Fly." Northwestern University & QuesTek Innovations LLC. Evanston, Ill. April 6. Available at http://www.transportation.northwestern.edu/docs/2011/2011.04.06.BAC_Olson_Presentation.pdf. By permission from QuesTek Innovations LLC.

The computationally designed material, developed by QuesTek Innovations, achieved a high combination of strength, toughness, and resistance to both corrosion and stress corrosion. Actual design was achieved in 2 years using only five design prototype alloys, in contrast to the hundreds of alloys required for the traditional empirical development process. In terms of its specific properties meeting critical weight constraints, the Ferrium S53 alloy performs as well as advanced titanium alloys at a small fraction of the material and manufacturing cost.

The alloy was the first demonstration of the DARPA-AIM method in the flight qualification of a new material (see the description of the AIM initiative in Chapter 1). Using the iSIGHT process integration and design optimization software, sensitivity analysis was performed at the earliest stage of parametric design to minimize the propensity for property variation. At the same time, a "design-for-scale" approach constrained alloy composition

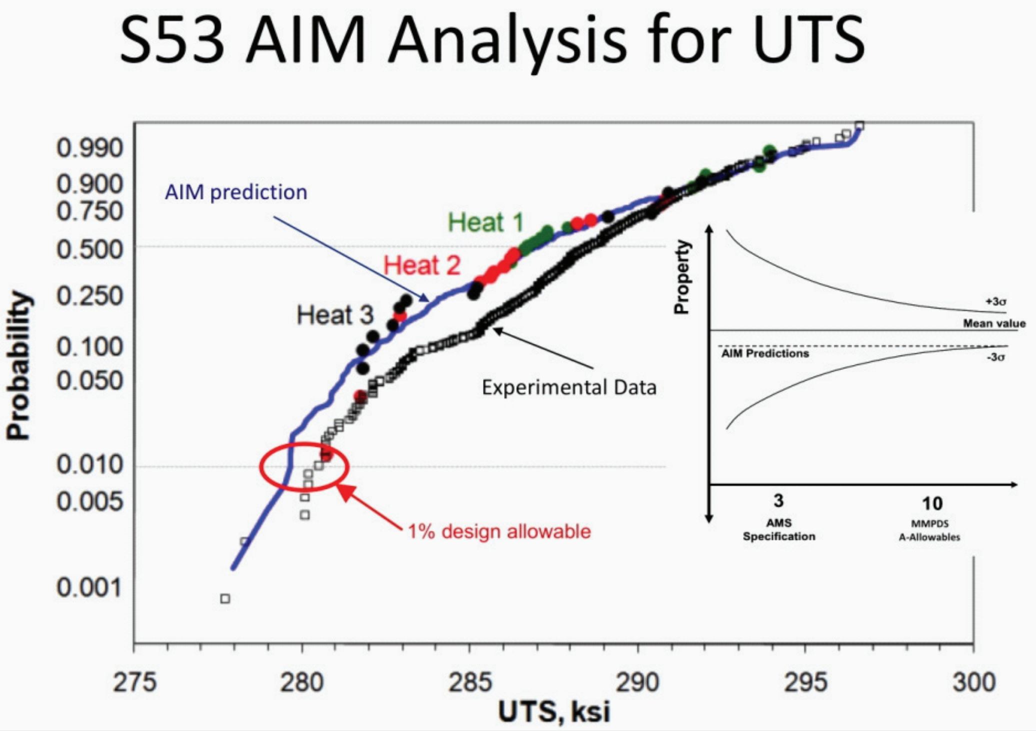

FIGURE 5-2-2 Forecast and measured cumulative distribution of ultimate tensile strength (UTS) for Ferrium S53. Inset represents the goal of forecasting variation validated at the 10 heat level of MMPDS specification from data on 3 heat level of AMS specification. SOURCE: G.B. Olson. 2011. “Computational Materials Design: Making CyberSteel Fly.” Northwestern University & QuesTek Innovations LLC. Evanston, Ill. April 6. Available at http://www.transportation.northwestern.edu/docs/2011/2011.04.06.BAC_Olson_Presentation.pdf. By permission from QuesTek Innovations LLC.

during all stages of development to the processability conditions viable at the largest required scale of ingot production. The approach successfully demonstrated the complete elimination of the scaleup component of alloy development—each scale ingot (from 3 lb to 15,000 lb) was produced with the required microstructure and properties the first time, without the usual multiple iterations to find a processable composition at each scale.

Figure 5-2-2 illustrates the simulation. Design of this alloy went from a clean sheet of paper to flight qualification in just 8.5 years. The developers stated that this could have been accomplished in 5 years if support had been continuous. The project’s sponsor estimated a cost savings of $50 million relative to traditional empirical development of the Strategic Environmental Research and Development Program.[2]

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[1] G.B. Olson, 1997. “Computational Design of Hierarchically Structured Materials,” *Science*, Vol. 277, No. 5330, pp. 1237-1242. See also C.J. Kuehmann and G.B. Olson. 2009. “Computational Materials Design and Engineering,” *Materials Science & Technology,* Vol. 25, No. 4.

[2] DoD-EPA-DOE. 2003. *Strategic Environmental Research and Development Program (SERDP) Bulletin,* Winter, No. 15, p. 6.

Box 5-3
ICME Example: Development of Superalloy GTD262 at GE

GE was one of the three companies that carried out a DARPA-AIM project, which facilitated the adoption of the AIM/ICME approach inside the company. During the AIM project, extensive testing was performed on the reliability of thermodynamic databases in predicting phase stability in multicomponent superalloys,[1] which resulted in a rigorous assessment of the fidelity level of thermodynamic data for several key phases.

A GE-funded project was initiated in 2002 and executed by both GE Global Research and GE Energy to replace tantalum (Ta), a critical refractory element subjected to high risks of supply and price disruptions, in superalloy GTD222, which was widely used in nozzles and vanes in GE power generation gas turbines. Using the AIM/ICME approach, especially by integrating computational thermodynamic predictions of phase equilibria with GE's materials property models and databases, Jiang and his collaborators designed four alloys with niobium (Nb) replacing Ta and with modifications to the concentrations of other elements to optimize and balance key properties and producibility.[2] Laboratory-scale tests were performed on those four Ta-free alloys for mechanical properties, oxidation resistance, weldability, and castability. The best of the four alloys doubled creep-resistance performance; other properties remained comparable to those of the Ta-bearing GTD222. It was subsequently subjected to an industrial-scale production trial (Figure 5-3-1) and successfully passed the qualifications without any technical hurdles. The new alloy was named GTD262; it was successfully introduced into GE power generation gas turbines starting in 2006, and it is experiencing much wider adoption today.

The first key lesson learned from this project is that reliable thermodynamic databases are essential to the design of multicomponent alloys and that fidelity tests are required to increase the confidence level for the predictions in specific regions of compositions. High-confidence thermodynamic predictions not only eliminated several of the experimental iterations that are usually needed to obtain the right alloy compositions (GTD262 was designed without even a second round of experimental trials), but also eliminated the long-term thermal exposure experiments that are generally required to test the propensity to form detrimental phases. GTD262 was developed and introduced in about 4 years from concept to industrial production (including design property data gathering) at less than 20 percent of the typical alloy development cost, which is very likely a record in both speed and cost in insertion of a new alloy into a gas turbine.

The second key lesson is that integration of thermodynamic predictions with property predictions from physics-based models and regression-based property databases is vital to the balance of properties. GE's proprietary models and internal databases played an important role in the development of GTD262. More widely applicable, physics-based, but experimentally validated microstructure and property models as well as higher-fidelity databases (especially thermodynamic databases with higher accuracy and wider compositional validity) are badly needed for the development of new alloys whose compositions differ vastly from those of existing alloys.

Early engagement with production/application teams at GE Energy in terms of multiple design goals and manufacturability has contributed significantly to the rapid and smooth transition from laboratory to production, which was another important lesson learned from the prior DARPA-AIM project. The rapid development of GTD262 is the first successful landmark that has helped establish within GE the credibility of computational

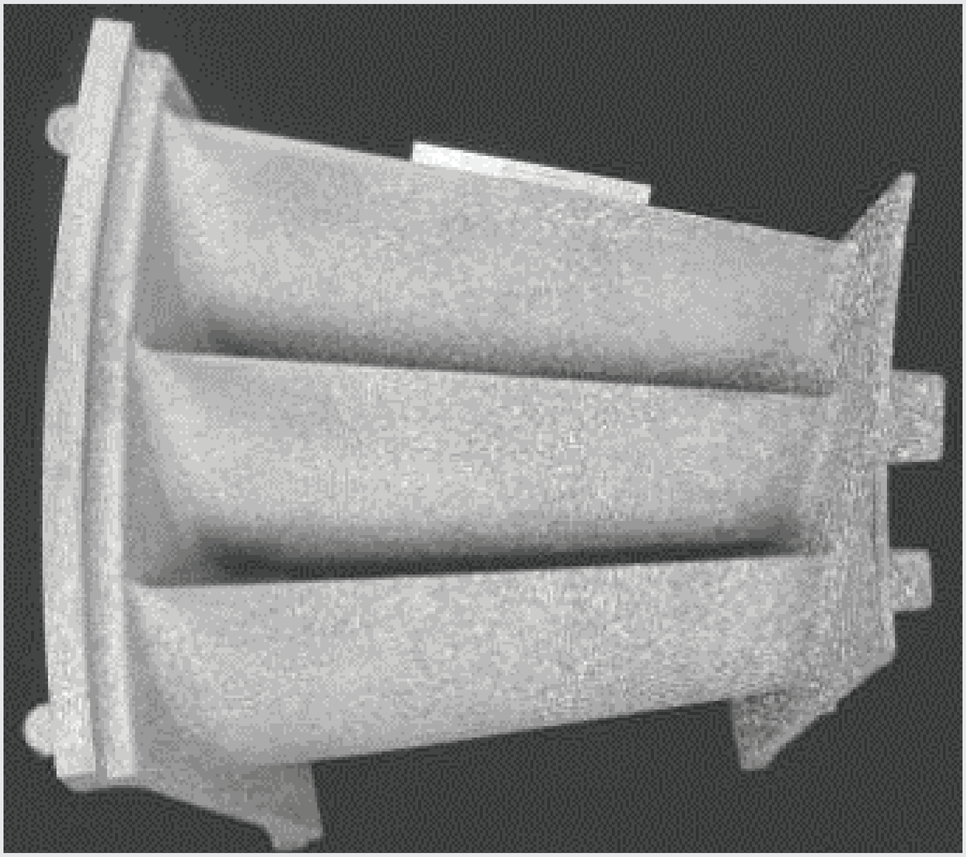

FIGURE 5-3-1 A production trial gas turbine nozzle made up of a new superalloy, GTD262. SOURCE: Courtesy of the General Electric (GE) Company.

alloy design and its associated methodologies, models, and databases. GE teams have since successfully designed and deployed into GE products new superalloys at similar high speed and low cost as a result of using the same AIM/ICME approach, which has now firmly established a vital role in new alloy development at GE.

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[1] J.-C. Zhao and M.F. Henry. 2002. “CALPHAD—Is It Ready for Superalloy Design?” *Advanced Engineering Materials*, Vol. 4, No. 7, pp. 501-508.

[2] L. Jiang, J.-C. Zhao, and G. Feng, 2005, “Nickel-Containing Alloys, Method of Manufacture Thereof,” and articles derived therefrom, World Patent Application WO2005056852, filed on September 29, 2004, published on June 23, 2005; U.S. Patent Application 20100135847, filed on October 21, 2009, published on June 3, 2010.

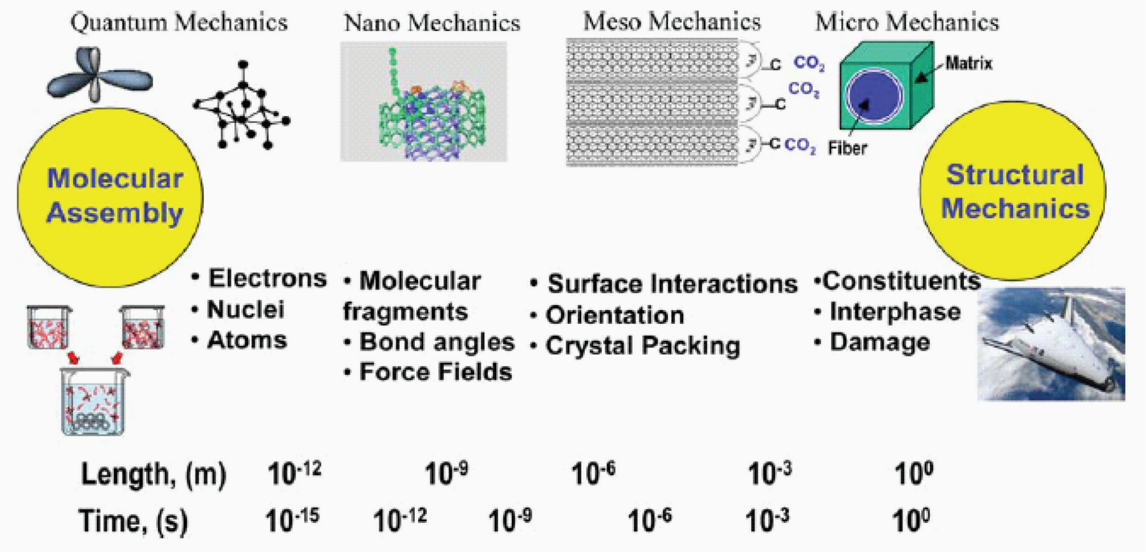

FIGURE 5-7 Schematic illustration of relationships between time and length scales for the multiscale simulation methodology. SOURCE: Adapted from T.S. Gates, G.M. Odegard, S.J.V. Frankland, and T.C. Clancy, 2005, "Computational Materials: Multi-scale Modeling and Simulation of Nanostructured Materials," *Composites Science and Technology,* Vol. 65, pp. 2416-2434.

strength of the composites, micromechanics and three-dimensional failure models are used, based on additional data from coupon-level testing. The models can be used to tune toughness qualitatively based on resin chemistry, but they are not yet quantitatively predictive (see Chapter 3 for additional details). The length scales over which modeling is required are illustrated in Figure 5-7.

A significant gap arises between molecular-level modeling and the modeling of final structural properties of the composite based on continuum assumptions. A major difficulty arises in the prediction of the local properties of the polymer near the fiber and nanoparticle interfaces as a function of resin chemistry and processing conditions. (Complexities of the modeling challenges are illustrated in Figure 5-8.) Another difficulty is that even the relative dispersion of nanoparticles within a resin/composites cannot be predicted as a function of particle type, size, and processing. Yet, since these composites are systems of interfaces with nearly all polymer existing in the neighborhood of interacting surfaces (fiber and/or nanoparticle), these local polymer properties are critical. Therefore, traditional composite modeling theories based on fiber layup must use coupon-level properties from unidirectional specimens in order to build up properties of the composites. Finally, although prediction of stiffness of composites based on traditional continuum and micromechanics modeling theories is well developed, predictions of more challenging properties, such as strength, toughness, and ballistic performance, need significant attention. Thus, while progress is being made, the existing gaps in modeling preclude the goal of being able to predict a composite system's properties based purely on knowledge of the individual constituents and the processing history. Significant progress in implementing composites as tailored lightweight solutions in a wide variety of structural applications will require the ability to design the material composition and processing to obtain desired properties.

5.4 TRANSITION OF LIGHTWEIGHTING TECHNOLOGIES INTO FIELDED SYSTEMS

Introduction of new technologies into complex systems typically requires significant experimental testing from the level of materials to coupons to components to subsystems. While modeling can accelerate this process, ultimately the new technology must be tested in field conditions as part of a complete system. Because lightweight materials are often considered a risk in terms of strength and fatigue life, many new technologies are first

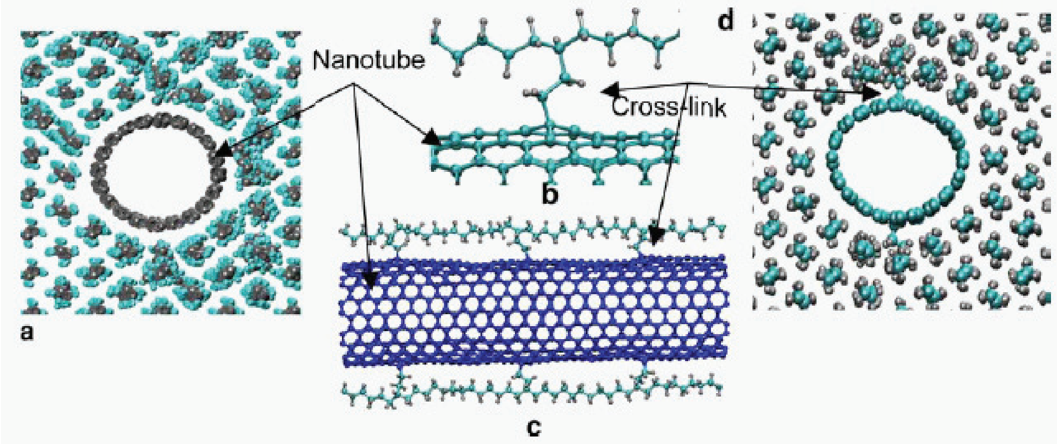

FIGURE 5-8 Representative volume element for modeling a nanotube-reinforced composite of polyethylene. SOURCE: T.S. Gates, G.M. Odegard, S.J.V. Frankland, and T.C. Clancy, 2005, "Computational Materials: Multi-scale Modeling and Simulation of Nanostructured Materials," *Composites Science and Technology,* Vol. 65, pp. 2416-2434.

incorporated into legacy platforms in non-critical, secondary components. For example, as discussed in Chapter 2, polymer composites were incorporated in aircraft air intake components before being used in primary structures such as wings and fuselage. In other cases such as lightweight ballistic and blast protection for ground vehicles, new ceramic and composite plates were simply bolted or adhered onto existing doors and undercarriages in place of steel. Designing systems to facilitate selection from many component options, depending on function and availability (e.g., the "A+B" approach described in Chapter 1), can speed up the adoption of new technologies.

For much greater leaps in system capability, however, the use of advanced technology demonstrations[26] can bring together interdisciplinary teams that strive for revolutionary advances (see Chapter 1 and Box 5-2). ATDs can be characterized as relatively large scale both in resources and complexity and as enabling enhanced military operational capability, operator/user involvement from planning to final documentation, testing in a real and/or synthetic operational environment, a finite schedule (e.g., 3-4 years), and the need to meet mutually agreed upon cost, schedule, and objective performance baselines such that there is a rapid transition to deployment.

The recent revision to the *Defense Acquisition Guide,* through DOD Instruction 5000.02, actually calls for ATDs in the preacquisition phase of development—that is, before Milestone B, in the technology development phase. This would seem to be a good opportunity to integrate ICME methods to accelerate design and development of prototypes for ATDs, especially for lightweighting materials and their integration with structural requirements and design configurations.

ATDs offer an important opportunity to use system engineering and design optimization and it would be wise to take maximum advantage of this opportunity. To ensure that this is done, ATDs should use a gated approach to development that includes all of the requirements that an actual, fielded system would have to meet. Although, because it is an ATD, not all of these requirements would need to be validated by test, there should be clear direction as to how the requirement would be met in a production vehicle. Additionally, where feasible, ICME tools can be used in ATDs to accelerate the early stages of design and optimization and to improve the robustness of the final hardware.

ATDs have potential to be very good vehicles for evaluation of lightweighting concepts, especially integrated materials and configuration concepts. ICME investment, especially related to lightweighting materials technolo-

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[26] Note that ATDs are but one process for facilitating the transition from technology development to deployment. For others, see (for example) the list at http://www.onr.navy.mil/en/Science-Technology/Directorates/Transition/Technology-Transition-Initiatives-03TTX.aspx. Some of these other initiatives may also provide opportunities to develop and transition lightweighting materials and designs.

gies, would facilitate success through accelerated assessment and analytical prediction of new material behavior. This would enable an ATD (or prototype) to be designed and manufactured with reduced risk and on an accelerated schedule.

As noted in Chapter 4 in the discussion of the JLTV competitive prototyping program, and of virtual prototyping, such a step—to try out new materials and new designs for lightweighting in terms of their effects on other attributes—could be considered in the "pre-ATD" or "pre-prototyping" stage. The design solutions that look the most favorable could then progress to the ATD stage or physical prototyping stage.

ATDs have brought about revolutionary military vehicles. For example, UAVs, advanced ship configurations, and lightweight vehicles are technologies that emerged from ATD projects begun in the 1990s. But not every ATD has proven to be a resounding success. Lightweight transport vehicles for the Army proved to be vulnerable to IEDs and assault weapons because of inadequate armor,[27] and UAVs suffered from poor ground station interfaces and required inordinate maintenance. Some of the problems encountered with these vehicles can be attributed in part to their hasty introduction into service, despite their having been intended as demonstration vehicles only. Evidently the protocols used to "graduate" ATDs from demonstrators to fielded systems proved inadequate.[28] An excellent set of recommendations for bridging the gap between ATDs and fielded systems is detailed in a previous NRC report.[29]

5.5 MANUFACTURING AND MAINTENANCE TECHNOLOGIES THAT FACILITATE LIGHTWEIGHTING

Despite the fact that the United States has been the innovator of virtually all major manufacturing technologies for defense products in the post–World War II era, there is widespread realization that the competitiveness of the U.S. manufacturing industry has declined over the last 20 years. One consequence is that the U.S. defense industry has had to rely more on global manufacturers for supply of raw materials, intermediate goods, and many niche products.[30]

The ability of the DoD to "lightweight" will be dependent to some extent on the preservation and nurturing of the domestic manufacturing base. It would also benefit significantly from a parallel commercial base for air, sea, and land transport systems. Parallel markets would have the effect of reducing risk across all stages of technology and manufacturing readiness and reducing associated costs. This trend has indeed been observed historically, wherein the "knowledge spillovers" from the commercial sector have resulted in military systems with longer service lifetimes.

While advances have been made in reducing raw material cost through DoD efforts (e.g., the Title III Program on National Defense Industrial Resources Preparedness), the secondary processing methods for many newer material candidates or product forms have not matured and are relatively undeveloped compared with those for steel (e.g., see Table 5-3). For example, robust manufacturing processes for fabricating complex structural components from continuous-fiber-reinforced composites have not yet achieved the rates and consistency of steel stamping.

Titanium is also recognized as a leading candidate material for lightweighting, but its viability for broad use is questionable because of high acquisition costs and risks associated with its availability. Since no single military application will raise demand for such materials to support and sustain production levels, there is a need to leverage demand with the commercial industry.

It is important to note that investments in fundamental research that leads to exciting new materials typically

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[27] Dick Engwall, "First Army ACAT-1 Program TRL Review Including MRL Critique," briefing to NDIA Manufacturing Commmittee Meeting, November 2008. This briefing includes some excellent suggestions on how to change the current paradigm.

[28] Stew Magnuson. 2010. "New Truck to Show the Way for Acquisition Reforms." *National Defense Magazine*. August. Available at http://www.nationaldefensemagazine.org/archive/2010/August/Pages/NewTruckToShowTheWayforAcquisitionReforms.aspx.

[29] NRC. 2003. *Use of Lightweight Materials in 21st Century Army Trucks.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=10662.

[30] See, for example, RAND Corporation, 2004, "High Technology Manufacturing and US Competitiveness," March 20, papers at http://www.innovationpolicy.org/consolidating-the-multitude-of-reports-callin; and NRC, 1999, *Defense Manufacturing in 2010 and Beyond*, Washington, D.C.: National Academy Press, pp. 12-15.

do not translate to commercial products or military application for many decades because the R&D on the scalable processing of the material into functional forms follows at a much later stage. Accelerated use of new materials requires parallel investments in manufacturing process R&D.

A critical need in the overall readiness of fielded combat systems is the "determination of remaining usable life and the quantitative prediction (i.e., prognosis) of future operating capability." This would mitigate the "fear of failure" in the war theater and give commanders the "ability to adaptively manage and deploy combat systems that might otherwise be removed from service."[31] In simple cost terms, extending the service life of a component with a conservative 6-year life by 2 years reduces the cost of that component by 25 percent. There are also significant operational benefits. A good example of this is the (now-canceled) Future Combat System (FCS) program.[32] Here the requirements for reliability and operational availability were to be met by employing a prognostics-based approach to maintenance, allowing decisions to be made to replace critical parts vulnerable to failure just before they fail or before an upcoming mission. Such condition-based maintenance (CBM) approaches are becoming more widespread within U.S. industry and the U.S. military.

"A complete CBM system requires the integration of a variety of hardware and software components,"[33] as demonstrated by an ongoing project titled "Light Amphibious Vehicles—Sense and Respond Logistics Phase I, II, III, IV," organized by the National Center for Manufacturing Sciences under its Commercial Technologies for Maintenance Activities.[34] The platform itself, with monitoring and communications equipment onboard, senses vehicle health information and alerts the crew to vehicle status. The data are shared wirelessly with operations in the immediate vicinity. Remote technicians can then provide real-time guidance to on-site personnel about maintenance decisions.

The initial phases of this project have demonstrated that early warning has reduced maintenance cycle time by approximately 50 percent and increased fleet-wide operational availability by 7 percent. Maintenance cost avoidance exceeded $22 per mile based on overall preventive maintenance monitoring, and the vehicles are expected to see an overall 14 percent increase in mean time between failure. These improvements should continue to increase as further testing and optimization proceed.

5.6 AVAILABILITY OF LIGHTWEIGHTING MATERIALS

As noted in Chapter 1, two cornerstones of lightweighting are (1) low- or reduced-density, high-specific-performance[35] alloys, and (2) fiber-reinforced composite materials. A summary of the most important of these materials and their current status is provided in Table 5-3, which also includes high-strength steels, because even modest improvements in steel strength can have a large impact due to the large amounts of steel used in military vehicles. Some alloys, such as those based on aluminum, are readily available. They are used widely in industry in sufficiently large volumes to support the operations of multiple suppliers.

Magnesium is a structural metal used only in low volumes because conventional processing of magnesium sheet is expensive and limited in availability and industrial capacity. Magnesium alloys, and components based on wrought magnesium, have not found widespread commercial or military use. Consequently, neither the United States nor Europe currently has adequate capabilities for producing these alloys or manufacturing magnesium components on a large scale. Domestic production capabilities that had previously been established have been

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[31] This section is drawn from information at http://www.acq.osd.mil/log/mpp/cbm+_related_links.html.

[32] The Future Combat Systems program was the Army's principal modernization program. U.S. Defense Secretary Robert Gates announced in April 2009 that he was killing the vehicle portion of the Army's $160 billion Future Combat Systems. FCS was originally envisioned as "a program that would create a group of brand-new super-brigades and outfit them with next-generation, hyper-connected vehicles and gear." See Kris Osborn, 2009, "FCS Is Dead; Programs Live On: U.S. Army to Dissolve Flagship Acquisition Effort," *Defense News,* May 18, available at http://www.defensenews.com/story.php?i=4094484.

[33] See http://www.acq.osd.mil/log/mpp/cbm+_related_links.html.

[34] "CTMA is a collaboration between the National Center for Manufacturing Sciences (NCMS), its member companies, and the DoD. Under a historic Cooperative Agreement between NMCS and OSD (L&MR) MPPR, NMCS and its member companies co-sponsor technology development, deployment, and verification with DoD organic maintenance activities." Excerpted from http://www.acq.osd.mil/log/mpp/cbm+_related_links.html. See that website for more information.

[35] Specific performance (e.g., strength) is performance divided by density.

TABLE 5-3 Current Status of Lightweight-Enabling Structural Materials

Material	Applications	Material Availability	Manufacturing Capability	Cost
Magnesium	Thick sections for armor	Limited domestic supply	Manufacturing capability for thick sections is lacking	High compared with aluminum
Titanium	Structures, armor, seawater systems	Adequate	Inability to join thick sections	Very high compared with steel, aluminum, and magnesium
Organic matrix composites	Ship superstructures Airframes and aero-engines Land vehicle structure Peripherals	Some limitation on fibers, especially domestically	Limited domestic capability for large-sections fabrication Lack of repair/joining to metal structure	Competitive
Ceramic matrix composites	Aircraft engines High-temperature structures	Very limited domestic sources of fibers, low capacity (predominantly Japanese)	Limited sources Manufacturing technology not mature	Extremely high
Metal matrix composites: (a) Fiber reinforced	Aircraft, engine structure Ship superstructure	Limited sources for fiber-reinforced metal matrix composites (MMCs)	Very limited sources and technologies	Very high compared with base metal alloys
Metal matrix composites: (b) Particulate reinforced	Land vehicle structure, peripherals	Limited sources for wrought MMCs	Limited sources and technologies	High compared with base metal alloys
Laminated ceramic structures	Transparent armor	Extremely limited (laboratory-level only)	Laboratory-level capability	Extremely high
High-strength steels	Lightweight automotive structures	High	High	Low

discontinued or the companies have gone out of business. This contraction in capability is due in large part to the excess production of magnesium in China and Russia during the 1980s and 1990s, the “dumping” of excess magnesium into U.S. markets, and the resulting global price reductions.[36]

Nevertheless, there have been some encouraging developments recently in processing for improvements in strength and toughness, making these materials even more competitive with aluminum and steel. For example, Nanomag TTMP—a processing innovation that is eco-friendly and produces ultra-fine-grain magnesium sheet—has led to significant improvements in strength and toughness, making these materials even more competitive with aluminum and steel.[37] In addition, there have been developments in equal channel angular processing that

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[36] G.J. Simandl, M. Irvine, and J. Simandl. 2007. “Primary Magnesium Industry at a Crossroads?” *Light Metal Age*, April, pp. 32-35.

[37] Nanomag TTMP is a new technology developed by Thixomat, Inc., and the University of Michigan for injection molding of magnesium sheet forms. See J. Huang, T. Arbel, L. Ligeski, J McCaffrey, S. Kulkarni, J. Jones, T. Pollock, R. Decker, and S. LeBeau, 2010, in *Magnesium Technology*, Warrendale, Pa: TMS; and R. Decker, J. Huang, S. Kukarni, and J. Jones, 2010, in *Materials Science Forum,* Vol. 654-656, pp. 574-579.

have demonstrated dramatic improvements in ductility.[38] Also, some new alloys have been developed that have very high strengths.[39]

Titanium alloys have long been used in aircraft and propulsion structures. They exhibit superior specific strength and elevated temperature capability relative to steels, without compromising specific stiffness. Titanium alloys are readily formable into sheet and bar forms and can be forged at elevated temperatures. However, for aerospace grades, the cost of titanium alloy is typically several times that of steel or aluminum alloys. A 2001 assessment revealed, "Just accounting for the extraction and processing costs to produce ingot, titanium is ~30 times more expensive per pound than steel and ~6 times that of aluminum. The cost gap for titanium widens when fabricating components and structures." [40] The extensive use of titanium in aerospace vehicles is testament to the cost premium on lightweighting that the industry can bear. Although significant weight benefits could be achieved through the use of titanium alloys in land vehicles and ships, their high cost and a somewhat limited production capability severely restrict their use in these areas.

Carbon fibers have been used extensively as reinforcements in polymer matrix composites. These fibers have been central to the development of composite airframes for the Boeing 787 and Airbus 380 aircraft. Nonetheless, there are now fewer suppliers of carbon fiber than there were a decade ago. In addition, there are few fiber manufacturers today making the high-modulus and ultra-high-modulus fibers that will likely be in greatest demand in future DoD programs. Furthermore, there is not much spare fiber production capacity. The latter deficiency was made clear, for instance, in the worldwide shortage of carbon fiber that followed large-scale efforts in Japan to seismically retrofit all bridge and elevated roadway supports with wound carbon fiber braces,[41] following the Hyogoken-Nambu earthquake in 1995. The availability and sourcing of high-performance carbon fibers has been a long-term concern for the DoD; the National Defense Authorization Act has, on two occasions (2001 and 2005), directed the Secretary of Defense to prepare an assessment for the Committees on Armed Services of both the House and the Senate.[42]

The limited availability of high-temperature silicon carbide fibers presents a more dire problem. These are being investigated primarily as reinforcements in ceramic matrix composites for aircraft engines and future high-performance military applications such as rocket nozzles and scramjets. The available volume of these composites is currently small, and there is no large-scale manufacturer of these fibers outside Japan. The maximum temperature capabilities of these silicon carbide fibers are also limited (to about 1300-1400°C, depending on service life). Continued and sustained development of new fibers will be necessary to reach the targeted temperature capabilities (above 1500°C).

Polycrystalline oxide fibers, based on sol-gel derived alumina and mullite, have been developed by 3M Company under joint funding with DARPA for use in high-temperature ceramic composites. Although the temperature capabilities (1100-1200°C) of current state-of-the-art oxide fibers are well below the target, these fibers have found commercial application as reinforcements for aluminum alloy cables for power transmission, displacing steel-core, aluminum-braided power cables.

The availability of polymer-based fibers used in armor, such as Kevlar, is of less concern. Kevlar is very widely used in a variety of commercial applications that do not depend on DoD support. Furthermore, the manufacturer (DuPont) is an exceptionally large, domestic company. Another fiber—based on highly oriented, high-molecular-weight polyethylene and sold under the trade names Dyneema (DSM) and Spectra (Honeywell)—exhibits very low density (less than 1 g/cm^3) and exceptional strain-to-failure, or percent elongation before breaking (2.9 to 3.5

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[38] W. Kim, C. An, Y. Kim, and S. Hong, 2002, *Scripta Materialia,* Vol. 47, pp. 39-44; Y. Yoshida, K. Arai, S. Itoh, S. Kamado, and Y. Kojima, 2005, *Science and Technology of Advanced Materials,* Vol. 6, pp. 185-194; and T. Mukai, M. Yamanoi, H. Watanabe, and K. Higashi, 2001, *Scripta Materialia,* Vol. 45, pp. 89-94.

[39] K.Y. Zheng, J. Dong, X.Q. Zeng, and W.J. Ding, 2008, *Materials Science and Engineering A,* Vol. 489, p. 103; B. Smola, I. Stulíkova, F. von Buch, and B.L. Mordike, 2002, *Materials Science and Engineering A,* Vol. 324, p. 113; and S.M. He, X.Q. Zeng, L.M. Peng, X. Gao, J.F. Nie, and W.J. Ding, 2007, *Journal of Alloys and Compounds,* Vol. 427, p. 316.

[40] B. Hurless and F.S. Froes. 2002. "Lowering the Cost of Titanium." *AMPTIAC Quarterly*, Vol. 6, No. 2. Available at http://ammtiac.alionscience.com/pdf/AMPQ6_2ART01.pdf. Last accessed June 21, 2011.

[41] T. Ogaata and K. Osada. 2000. "Seismic Retrofitting of Express Bridges in Japan." *Cement and Concrete Composites*, Vol. 22, pp. 17-27.

[42] "Polyacrylonitrile (PAN) Carbon Fibers Industrial Capability Assessment, OUSD (AT&L) Industrial Policy," October 2005. Available at http://www.acq.osd.mil/ip/docs/pan_carbon_fiber_report_to_congress_10-2005.pdf.

percent).[43,44,45] This fiber shows considerable promise for composites in armor systems. Yet the full potential of these fibers has yet to be realized in commercial products. Theoretical considerations and laboratory-scale demonstrations indicate that strength elevations of more than 50 percent could be achieved in the next generation of commercial fibers. This goal will require a robust research effort and sustained resources to bring it to fruition. See Section 5.3.3 for an example of the challenges involved in modeling the behavior of polymer composite materials.

Finally, although high-strength steels may not immediately be recognized as materials for lightweighting, the design of new steel compositions with even modest strength improvements (10 to 20 percent), combined with design optimization and manufacturing innovations, can have significant impact in creating lighter structures. The benefits are derived in part because of the large use of steels in military vehicles. However, the lack of availability of new steels and of large-scale production remains an impediment to their wider use in military vehicles and components.

5.6.1 Design Expertise in the Process Industry Sectors

From 1998 to 2008, the U.S. Department of Energy's Office of Industrial Technologies (renamed the Industrial Technologies Program, ITP) partnered with trade organizations representing the nine energy-intensive industries on which the branch has focused its R&D portfolio in order to identify common needs, concerns, and visions for long-term investment and partnering:[46] Elaborate roadmaps for new technology development were created with each of the nine industry groups, of which the five groups relevant for the current NRC lightweighting study are aluminum, glass, steel, metal casting, and chemicals. These roadmaps identified near-, mid-, and long-term R&D priorities, performance targets, and programs to advance the state of these "industries of the future" with the aim of strengthening U.S. capabilities and efficiencies in the supply of these base materials to domestic manufacturers.

Each roadmap generated grand challenges that have resulted in numerous internal R&D and cross-industry collaborations involving leading material suppliers, which in turn generated a great deal of material and design knowledge that is in the private and public domains. The respective trade associations—e.g., the Aluminum Association, Steel Industry Market Development Institute, Glass Manufacturers Association, and American Chemical Society—have archived and disseminated much of the information through project reports. Such vital information can be drawn upon by military manufacturers to initiate new R&D in design, manufacturing, and demonstration of system-level lightweighting solutions. Examples of high-priority material and processing research include:[47]

- Computer design tools;
- High-temperature materials, including refractories;
- Casting, advanced forming, and tool and die materials;
- Databases and process modeling;
- Joining and welding;
- Coating properties, processing, and applications;
- Mold and die filling;
- Ceramic and composite reliability and performance data;
- Erosion- and corrosion-resistant materials and coatings;
- Materials for sensors; and
- Separation methods, recycling, waste, and by-product treatment.

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[43] Keith McDaniels, R.J. Downs, Heiner Meldner, Cameron Beach, and Chris Adams. 2009. "High Strength-to-Weight Ratio Non-Woven Technical Fabrics for Aerospace Applications." Cubic Tech Corporation, Mesa, Ariz. Available at http://www.cubictechnology.com/Technical%20Fabrics%20for%20Aerospace%20Applications.pdf.

[44] "A Constitutive Model for DYNEEMA UD Composites," available at http://www.iccm-central.org/Proceedings/ICCM17proceedings/Themes/Materials/HIGH%20PERFORMANCE%20FIBRES/D6.9%20Iannucci.pdf. Accessed October 21, 2011.

[45] Honeywell Spectra Fiber 1000 Product Information Sheet. Available at http://www51.honeywell.com/sm/afc/common/documents/PP_AFC_Honeywell_spectra_fiber_1000_Product_information_sheet.pdf.

[46] DOE-EERE, OIT, 2000, *Program Plan for Fiscal Years 2000 Through 2004, Industrial Materials of the Future*, July; NRC, 2000, *Materials Technologies for the Process Industries of the Future: Management Strategies & Research Opportunities*, Washington, D.C.: National Academy Press.

[47] Richard Silberglitt and Jonathan Mitchell. 2001. *Industrial Materials of the Future (IMF) R&D Priorities*. Rand Corporation study for NREL.

5.7 CONCLUSION

Despite the seemingly disparate considerations in lightweighting of the full spectrum of military vehicles, important commonalties are evident. Future policies and investment strategies that are founded in these commonalties should yield the greatest impact on lightweighting of future military vehicles.

Furthermore, with the enormous magnitude of military operations and associated costs, such strategies are expected to have a broad impact on national concerns that extend beyond the military: notably, the sustainability of fossil fuel use at present levels, the balance of trade, and domestic employment opportunities.

6

Findings and Recommendations

The NRC Committee on Benchmarking the Technology and Application of Lightweighting was asked to (1) assess the relevance of the definition of lightweighting within the materials community; (2) assess and benchmark the current state of lightweighting implementation in land, sea, and air vehicles, focusing on military applications; and (3) recommend ways in which use of lightweight materials and solutions might be better implemented.

Although the committee found good examples of vehicle lightweighting in all three areas (air, sea, and land), its review of barriers and opportunities indicates that there is still much that can be done. Viewing lightweighting broadly, and at the systems level, may help bring these opportunities to light. In this chapter, the committee describes its view and definition of lightweighting and offers some recommendations for how lightweighting might be better implemented in military vehicles.

6.1 DEFINING LIGHTWEIGHTING

The committee believes that lightweighting has been viewed narrowly in terms of both benefits and mechanisms. It adopted a broad view of lightweighting, recognizing it as a means of achieving not only reduced fuel consumption and costs and the associated logistical requirements, but also a variety of other desirable features. The committee defined lightweighting in military systems[1] as follows:

> Lightweighting is the process of reducing the weight of a product, component, or system for the purpose of enhancing certain attributes, notably (1) performance capability, (2) operational supportability, and (3) survivability.

In the committee's view, lightweighting should be a means not only of reaping the benefits of improved fuel economy but also of achieving an improved vehicle. The goals of lightweighting can include better performance, in areas such as vehicle speed, maneuverability, payload capacity, and range; easier and less costly operational supportability, encompassing fuel consumption as well as transportability, durability, reliability, maintainability, and repairability; and improved survivability, in forms such as resistance to blast and ballistic threats, tolerance

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[1] Although this definition also applies to civilian vehicles, the main focus of this report is military vehicles, and so the attributes of interest and the wording used are tailored for military applications.

of damage and environmental conditions, and avoidance of detection. Lightweighting can also confer a further benefit in the form of flexibility and adaptability.

The means of reducing vehicle weight has also been viewed narrowly, as a process of replacing the materials in a system with lighter[2] alternatives. Although this is indeed one approach to reducing weight, lightweighting can be achieved in many other ways: for instance, by changing structural shape or tailoring the spatial configuration of dissimilar materials (as is done with fiber composites and sandwich panels) to make the most efficient use of each material.

Most importantly, lightweighting can be achieved at a systems level, which involves considering the potential for lightweighting from the beginning of the design process. For example, creative architectural designs that involve multifunctionality in components or make use of multifunctional materials can emerge when lightweighting approaches are integrated into the engineering of new systems. A systems-level perspective also incorporates considerations such as the availability of new or advanced manufacturing methods that enable the development and processing of new materials and materials combinations, the production of shaped parts from the materials, and the reduction of manufacturing defects (which improves durability and service life).

System engineering design could support the use of more aggressive design strategies to optimize structure and function, based on (1) optimization of system design and topology using available or new technologies and components, (2) improved understanding of response and failure mechanisms of materials, (3) improved associated physics-based computational models, and (4) improved associated tools for prediction of product performance and life.

The committee notes that strategic, national-level concerns can be addressed in part by lightweighting, or can seriously impede lightweighting. The committee identified three of these concerns as having particular strategic importance: (1) the protracted time required to develop and field military vehicles; (2) unsustainable energy use, which has implications for both military operations and long-term national security and economic prosperity; and (3) the declining domestic capability for manufacturing, which threatens the ability to achieve lightweighting. The committee notes that programs to support the manufacturing capabilities needed to produce lightweighting technologies could also constitute part of a national strategy to rebuild cutting-edge manufacturing capabilities in the United States. Table 6-1 illustrates the relationship between these national-level concerns and the committee's definition of lightweighting.

Below, the committee offers five recommendations for improving the implementation of lightweighting in military (and civilian) vehicles. They reflect the committee's broad view of lightweighting and what it can accomplish. The connections between the three national concerns outlined above and these five recommendations are shown in Figure 6-1.

6.2 DIGITAL DESIGN TOOLS FOR SYSTEMS ENGINEERING

Finding 1: One consequence of lengthy acquisition processes is that changes in threats and operational requirements in areas of conflict can outpace the development of new military vehicles and vehicle technologies. The ability to keep up with evolving requirements could be improved by both reducing the time required for development and improving the capability to design flexibility and adaptability into vehicle systems. Both goals require increased capability in digital design, especially for the integration of materials and design configurations. Such capability could significantly improve the effectiveness of current systems engineering processes.

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[2] "Light" and "lightweight" as used in this report denote materials having high specific properties (e.g., high specific strength, defined as strength divided by density) or, more generally, high specific performance. Historically lightweighting has been achieved by focusing on lower-density materials with high property values (e.g., composites). However the converse is equally viable—using traditional-density materials with enhanced property values, which then allow reduced total weight via reduced cross sections.

TABLE 6-1 Relationship Between National Concerns and the Committee's Definition of Lightweighting

National Concerns	Vehicle Characteristics That Can Be Enhanced by Lightweighting	Connection
Protracted time to develop and field new military vehicles	Performance Survivability	The long time periods required to develop new vehicles as well as new materials prevent both (1) responses to evolving threats, which may require new or better performance and survivability, and (2) the rapid integration of new materials, technologies, and designs that could provide these improvements.
Energy use	Operational supportability	Energy use in military vehicles is unsustainable. Lower fuel use means reduced energy costs and less exposure to risk associated with supplying fuel to deployed forces. Reduced dependence on petroleum fuels reduces concerns about national energy security and about economic stability.
Declining domestic capability for manufacturing	Performance Survivability	Lack of domestic capability to produce new materials and the parts made from them hinders the U.S. ability to realize the full benefits of lightweighting. Increasing this capability would help to improve the national manufacturing picture.

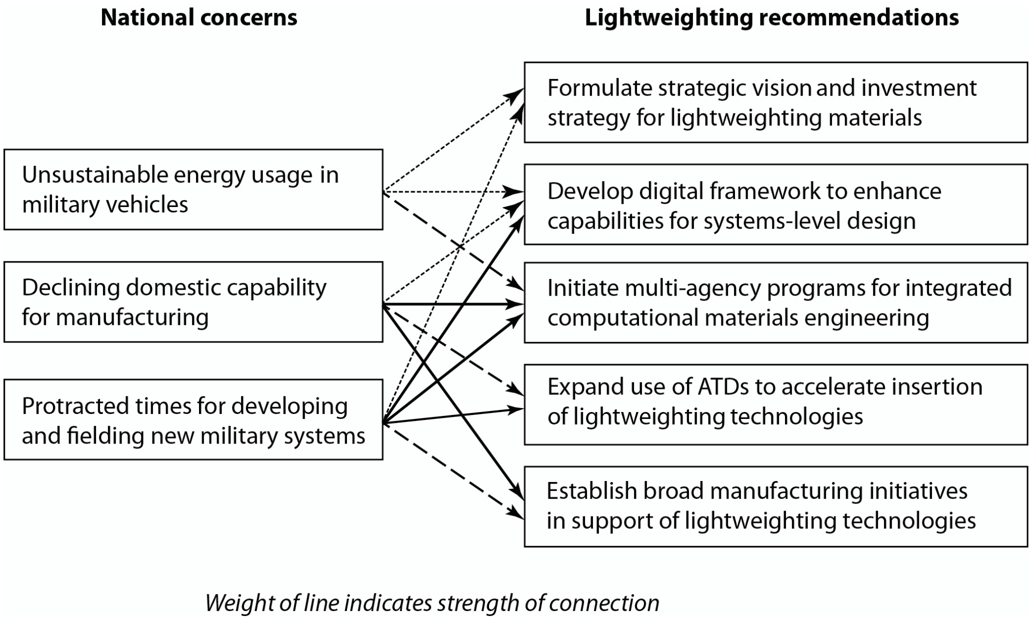

FIGURE 6-1 National concerns and associated lightweighting recommendations.

Recommendation 1:[3] The DoD should initiate a program to develop and integrate high-fidelity models of materials, processes, and performance into a comprehensive digital system-design process for future air, maritime, and land vehicles. Although many individual models exist or are being developed, these models often are not integrated, and the focus of a larger organization such as the DoD is required to facilitate coordination.

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[3] During the course of this study, the Obama Administration announced the new Materials Genome Initiative, which addresses many of these needs. See Box 6-1.

Box 6-1
The Materials Genome Initiative

During the course of this study, President Obama announced a 10-year initiative, the Materials Genome Initiative, a "new, multistakeholder effort to develop an infrastructure to accelerate advanced materials discovery and deployment in the United States."[1] This ambitious initiative is expected to significantly advance integrated computational materials engineering (ICME) tool development and provide the materials innovation infrastructure that this committee believes is needed as well as develop the work force. Development of ICME capabilities aimed at materials problems of pressing national importance is explicitly included in this initiative.

The committee's recommendations 1, 2a, and 2b could be addressed by making the development of models and ICME tools needed for lightweight materials and lightweight vehicle design a prominent activity within this initiative. Such capabilities would have obvious dual uses within the commercial vehicle sector.

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[1] Office of Science and Technology Policy. 2011. "Materials Genome Initiative for Global Competitiveness." June. Available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf.

This process would have numerous benefits, including:

- Significant reduction in the time required to implement new lightweighting solutions;
- Reduction in the extent of manufacturing and testing required to critically assess new designs;
- Reduction in acquisition costs;
- A more rapid response to changing threat environments and vulnerabilities of military systems;
- A more comprehensive assessment of the tradeoffs among attributes related to weight and system performance;
- Accelerated insertion of new materials into military systems, potentially bringing into closer alignment the timing of the materials development cycle and the timing of product development; and
- Reduction in the risk and cost of advanced technology demonstration (ATD) projects.

Finding 2: In addition to the models themselves, a framework for their effective integration into the vehicle design environment is required. An important element of this framework is integrated computational materials engineering (ICME), a strategy that extends from materials design through structural design in an integrated fashion, thereby including the ability to design new materials as part of achieving optimal structural performance. In the committee's judgment, ICME tools and methods offer the greatest opportunity to accelerate the development and validation of new materials and processes for lightweighting, which would bring the current lengthy development cycle for these new materials and processes more into line with the generally much shorter design cycles for vehicles and products. Although numerous programs and specific applications have demonstrated the feasibility and benefits of ICME, broad development and implementation will require comprehensive, sustained effort and investment, along with coordinated actions among numerous stakeholders, to have a significant effect on future components, vehicles, and systems.

Recommendation 2a:[4] The DoD should expand its leadership role as a champion of ICME. It should develop and lead a comprehensive, sustained, multi-agency ICME program, with some specific focus on lightweighting materials and technologies. The program should:

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[4] During the course of this study, the Obama Administration announced the new Materials Genome Initiative, which addresses many of these needs. See Box 6-1.

- Identify and support foundational engineering problems[5] that specifically address lightweighting for air, maritime, and land applications;
- Foster the development and stewardship of national curated knowledge repositories relevant to lightweighting materials;
- Coordinate with other stakeholders in the training and education of an ICME workforce; and
- Support the development of a suite of predictive tools for materials manufacturing, sustainment, and maintenance. These should address processes, performance, and properties and should include physics-based materials models of behavior under extreme loading conditions.

To accelerate development and broaden the research base required for development of ICME tools, the committee recommends that the definition of DoD basic research be broadened to include development of the fundamental building blocks of ICME and materials design, as distinct from materials discovery.

The DoD and industry have invested in materials model development for many years, and several programs have successfully demonstrated the feasibility of developing and integrating selected materials, processing, and microstructure-property models with an overall benefit to component design and development for the selected cases.[6]

What has not yet occurred is the broad, systematic development and implementation of ICME across industry and government. The committee believes that such broad development and implementation would be enabled, especially for lightweighting materials technologies, by an initiative supporting these general areas:

- Physics and materials-science-based model development;
- Sponsorship of selected foundational engineering problems targeting specific material classes and applications (such as lightweight composite materials and structures), with an emphasis on integration of analytical tools;
- Development and implementation of comprehensive national databases for support of ICME development; and
- Guidelines and processes for verification and validation of ICME tools and for determination of their maturity. This is essential if such tools are to be integrated at a systems level with design, structural analyses, life (or durability) prediction, and determination of key attributes such as ballistic performance.

Development of linked models for ICME is needed for all materials. Approaches are developing, albeit slowly, for materials and structures used in commercial vehicles. A problem unique to military vehicles, however, is that they are required to operate and survive under extreme loading conditions. In this context, there appears to be a particularly acute need for new physics-based models to predict the behavior of materials under extreme loading conditions: principally under dynamic loadings (including the domain of high-strain-rate loading and shocks), but also at elevated temperature and in the presence of corrosive/oxidative environments flowing at high velocities such as those present in turbine engines. Numerical simulation tools (based, for example, on finite element methods) need to be extended beyond the existing commercial codes in order to properly account for the pertinent fracture phenomena and the corresponding length scales that characterize the fracture processes. The latter include extended or augmented finite element methods as well as particle-based computational methods. These methods are required for representation of phenomena such as damage-evolution, fragmentation, and comminution of materials under dynamic loading conditions. They could also be used to better understand complex fluid-structure interactions that occur, for example, when a buried explosive is detonated and the resulting shock wave and soil ejecta impact a ground vehicle. Such models would then enable substantially improved capability to design lightweighting into the vehicle while concurrently optimizing for survivability.

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[5] NRC. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12199.

[6] Leo Christodolou, DARPA, "Accelerated Insertion of Materials," presentation by to the NRC Committee on Integrated Computational Materials Engineering, November 20, 2006. Available at http://www7.nationalacademies.org/nmab/CICME_Mtg_Presentations.html.

Recommendation 2b:[7] The DoD should foster the development, maturation, and advancement of physics-based materials models as well as numerical simulation tools and codes.

6.3 TRANSITION OF LIGHTWEIGHTING TECHNOLOGY VIA ADVANCED TECHNOLOGY DEMONSTRATION PROGRAMS

Finding 3: Advanced technology demonstration (ATD) programs have, in numerous instances, proven to be successful in introducing breakthrough technologies into DoD platforms.

In contrast to the rigorous risk-reduction approaches taken for major engineering system development and certification, which require that new technologies be relatively mature at the time that critical system architecture decisions are made, ATDs allow for more aggressive pursuit of higher-risk, higher-payoff technologies with significantly reduced requirements for testing, validation, and certification. With the appropriate technical vision and management, ATDs could be equally effective in accelerating the implementation of lightweighting technologies.

There is increased risk involved in fielding ATD systems that have undergone less stringent testing and validation. But the risk can be mitigated in part by ensuring that all systems-level requirements are introduced and properly addressed early in the development of the new technology. Good management of a gated process is needed to ensure a continuing focus on system requirements and the military's operational capabilities. Advanced concept technology demonstrations (ACTDs) offer a proving ground for advanced concepts that may provide an opportunity to incorporate ICME tools and methods.

Recommendation 3: The DoD should expand the use of ATDs to implement lightweighting technologies rapidly in air, maritime, and land demonstration platforms. To improve the transition value of ATDs for lightweighting, it is important that the DoD incorporate all system and operational requirements into projects, so that lightweighting technologies can be fully optimized from the outset.

The committee proposes the following guiding principles for developing effective lightweighting ATD projects:

- Include material suppliers, manufacturers and end users as part of preliminary design integrated project teams.
- Develop a path to qualification, even if the technology does not actually undergo qualification.
- Address the overall requirements of the target platform in order to increase the likelihood of technology transition.
- Draw on technologies developed in the private/commercial sectors in which performance is at a premium (such as auto or boat racing).
- Reassess existing prescriptive requirements for legacy systems that may appear overly onerous and may preclude technology development and transition.
- Maintain sufficient flexibility in initial ATD design to accommodate improvements as the technology is being evaluated.
- Establish up-front the lightweighting targets and performance metrics as well as allowable cost premiums.
- Identify clear pathways for producing, fielding, and maintaining the technologies.
- To facilitate incorporation of lightweight materials and lightweight design early in the ATD process, incorporate available ICME tools into ATD projects during design, development, validation, and demonstration. Where such tools are lacking, their development should be conducted in parallel with the ATD.

The DoD may also wish to consider using ACTDs as a proving ground for using ICME tools and methods in the development of advanced technologies and concepts.

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[7] During the course of this study, the Obama Administration announced the new Materials Genome Initiative, which addresses many of these needs. See Box 6-1.

6.4 A DOD-WIDE INITIATIVE ON AFFORDABLE MANUFACTURING TECHNOLOGY TO FACILITATE LIGHTWEIGHTING

Finding 4: The cost of fielding military systems that incorporate lightweighting solutions is high in part because production volumes are low and performance requirements are highly exacting. The focus on reducing acquisition costs has resulted in increased reliance on foreign technology sources,[8] thus eroding U.S. strategic manufacturing advantages. The problems are exacerbated by the lack of parallel commercial markets that could significantly reduce the costs of technology development and make initial investments more attractive.

One consequence has been a continuing cycle of "boom-to-bust" for defense contractors. The aerospace industry has been somewhat successful in this regard, since lightweighting is almost equally important in commercial and military aircraft. In contrast, for ground vehicles (especially their protection systems), there are few parallel commercial markets. The military ship industry also lacks close commercial parallels. Notable exceptions include the Navy's joint high-speed vessel and the Lockheed Martin littoral combat ship, both derivatives of fast-ferry designs developed overseas.

The economic viability of fast ferries is extremely weight-sensitive. If a viable, national high-speed ferry network were to develop, it would have the potential to foster a domestic, competitive capability for manufacturing lightweight ships.

Recommendation 4a:[9] The DoD should establish broad manufacturing initiatives—using the ManTech program framework as a model—that encompass a variety of lightweighting strategies, materials, and technologies, with the goal of achieving quantum improvements in performance, affordability, sustainability, and reliability.

The manufacturing challenges to be addressed include joining technology, parts consolidation and miniaturization, tool-less fabrication of low-volume production parts (using, for example, rapid prototyping/additive manufacturing and direct-material deposition technologies), improved non-destructive evaluation methods, and virtual process modeling. The manufacturing technologies to be covered should include those needed for advanced materials that have been developed but are not yet used by the DoD or in the private sector. Consideration must also be given to enhancing domestic sources that produce structural commodities in product form (for example, plates, fibers, and resins) from raw materials.

Recommendation 4b:[10] In concert with other government agencies, the DoD should explore the merits and requirements of parallel commercial markets that could reduce the development and acquisition costs of military vehicles as well as accelerate the availability and use of lightweighting materials and technologies.

6.5 A STRATEGIC VISION FOR MATERIALS CRITICAL TO LIGHTWEIGHTING

Finding 5: The committee believes that there remains insufficient high-level DoD awareness of and strategic vision for ensuring sustained domestic supplies of materials that are essential to the realization of effective lightweighting and would facilitate revolutionary advances in military systems. Although there is growing recognition of the importance of individual metals and rare-earth elements, the domestic availability, supply, sustainment, maintenance, and manufacturing of lightweighting-enabling materials, such as high-performance SiC fibers,

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[8] "DOD Undertakes Crash Study on Defense Industrial Base," *Manufacturing & Technology News,* May 31, 2011, Vol. 18, No. 9, pp. 1-2; "DOD Industrial Policy Shop Adds Manufacturing to Its Mission," *Manufacturing & Technology News,* April 29, 2011, Vol. 18, No. 7, p. 7; "Rising Labor Costs in China Are Still 96% Lower Than Those in the US," *Manufacturing & Technology News,* April 15, 2011, Vol. 18, No. 6, pp. 3-4.

[9] During the course of this study, the Obama Administration announced the new Advanced Manufacturing Partnership, which could address many of these points. See Box 6-2.

[10] During the course of this study, the Obama Administration announced the new Advanced Manufacturing Partnership, which could address many of these points. See Box 6-2.

Box 6-2
The Advanced Manufacturing Partnership

During the course of this study, President Obama announced the Advanced Manufacturing Partnership, "a national effort bringing together industry, universities, and the federal government to invest in the emerging technologies that will create high quality manufacturing jobs and enhance our global competitiveness."[1] The partnership implements the recommendations of a report from the President's Council of Advisors on Science and Technology (PCAST), which calls for "a partnership between government, industry, and academia to identify the most pressing challenges and transformative opportunities to improve the technologies, processes and products across multiple manufacturing industries."[2]

Some or all of the present committee's recommendations 4a and 4b could be addressed within the context of this partnership.

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[1] White House. 2011. "President Obama Launches Advanced Manufacturing Partnership." Press Release. Available at http://www.whitehouse.gov/the-press-office/2011/06/24/president-obama-launches-advanced-manufacturing-partnership.

[2] Office of Science and Technology Policy. 2011. *Report to the President on Ensuring American Leadership in Advanced Manufacturing.* June. Available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf.

thick-section magnesium, and polyethylene fibers, must become targeted priorities of the DoD for lightweighting to become widespread.

One existing program, the Defense Production Act Title III program, includes a number of materials projects relevant to lightweighting, such as production of SiC powder for ceramic armor, low-cost titanium, and continuous-filament boron fiber, but does not include some of the materials and manufacturing processes that the committee believes would have the greatest impact on lightweighting.

Recommendation 5: In cooperation with other agencies, the DoD should establish a federal investment strategy that (a) determines which structural materials are most important to future lightweighting and (b) establishes the resources to ensure continuous development of these materials and their associated manufacturing processes.

As part of this holistic approach, the existing Title III program should be expanded to include a larger number of materials critical to lightweighting of military aircraft, vessels, and vehicles. In expanding the program, the DoD should recognize the need for the long-term, continuous development of these materials and of the manufacturing techniques and capacity needed to produce them.

Although many elements, such as titanium and magnesium, are readily available in Earth's crust, the high cost of their extraction, reduction, and processing restricts their widespread use, even when their properties are highly favorable for lightweighting. Advanced materials, such as SiC and C fibers, that would facilitate high-performance structural applications are not available in sufficiently large quantities domestically to be used in DoD platforms, despite their being synthesized in the laboratory. There is also a lack of domestic manufacturing infrastructure to fabricate the primary metal alloys or the intermediate engineering forms (sheet, plate, bar, and so on) and to manufacture final, shaped products. This lack of infrastructure affects the use of lightweighting materials in both the defense and civilian sectors. For instance, although there is a military specification for the use of thick-section magnesium alloy (AZ31) in ballistic armor applications, it is not used in existing platforms both because of its high costs and because there are currently insufficient sources of the alloy to be used for armor applications. Similarly, while engine manufacturers have identified SiC fibers as essential for future CMC applications, these fibers are manufactured in significant quantities only in Japan and are permitted for use only in restricted (non-weapon) applications by the U.S. government and U.S. industries.

6.6 CONCLUSION

In assessing the status of lightweighting in air, sea, and land vehicles, the committee found that there are good examples of lightweighting implementation in military vehicles. However, many opportunities still exist to take fuller advantage of this strategy. The committee notes that viewing lightweighting in a much broader sense than has traditionally been the case could help bring those opportunities to light.

The recommendations outlined above could help the DoD to capitalize on these opportunities. The committee notes that, because the recommendations address issues of broad national interest, they could have far-reaching benefits for the nation's energy use, balance of trade, and jobs.

Appendixes

Appendix A

Committee Biographies

L. Catherine Brinson, *Chair,* is the Jerome B. Cohen Professor of Engineering at Northwestern University, with a primary appointment in the Mechanical Engineering Department and a secondary appointment in the Materials Science and Engineering Department. After receiving her Ph.D. in applied mechanics in 1990 from the California Institute of Technology, Dr. Brinson performed postdoctoral studies in at the German Air & Space Agency. Since 1992 she has been on the faculty at Northwestern University. Her primary research focus is on the modeling and characterization of advanced material systems, including high-performance composites and intelligent materials. Her current research investigations involve studies of aging in polymeric-based systems, the nanomechanics of nano-reinforced polymers, the characterization of titanium foams for bone implants, and experiments and modeling of shape memory alloys, where investigations span the range of molecular interactions, micromechanics, and macroscale behavior. Dr. Brinson has received several awards, including the 2006 Friedrich Wilhelm Bessel Prize of the Humboldt Foundation, the 2003 ASME Special Achievement Award for Young Investigators, the 1995-1999 NSF CAREER Award, and the ASEE New Mechanics Educator Award; she has served as a member of the Defense Science Study Group (1998-1999) and is currently on the National Research Council's National Materials Advisory Board (2005-2010). She has served as a member of three NRC committees, chairing one of them. Dr. Brinson makes numerous technical presentations on her research, organizes symposia at many conferences, and has authored more than 60 journal publications. She is an active member of several professional societies and served for 5 years on the Society of Engineering Science Board of Directors, including 1 year as president of the society. She has also been an associate editor of the *Journal of Intelligent Material Systems and Structures* and the *Journal of Engineering Materials and Technology*.

John Allison (NAE) is a professor in the Department of Materials Science and Engineering at the University of Michigan. He recently retired from Ford Motor Company, where he was a senior technical leader in Research and Advanced Engineering. At Ford, he led teams focused on the science and technology required for low-cost, durable components fabricated from cast aluminum and magnesium alloys. A major focus of Dr. Allison's work is the development of a comprehensive suite of integrated computational materials engineering tools for modeling of cast metal components, with approaches ranging from casting process simulation to first-principle atomistic calculations. His research expertise is in processing-structure-property relationships, complex failure processes such as fatigue and creep in advanced metals, and material selection processes. His past work has included development of titanium, intermetallics, and metal matrix composites for the automotive industry. Dr. Allison joined

Ford Research Laboratories in 1983. His work prior to that included service as an officer in the U.S. Air Force at the Wright Aeronautical Laboratories and as a visiting scientist at the Brown-Boveri Corporate Research Center in Baden, Switzerland. Dr. Allison has more than 120 publications and four patents. He was the 2002 President of the Minerals, Metals, and Materials Society (TMS), a global technical society for materials professionals. He is a fellow of ASM and has received numerous awards, including the Arch T. Colwell Award from the Society of Automotive Engineers, the Henry Ford Technology Award, Ford Technical Achievement awards, Ford Innovation awards, and the Air Force Systems Command Scientific Achievement Award. Dr. Allison was elected to the National Academy of Engineering in 2011. He holds a Ph.D. in metallurgical engineering and materials science from Carnegie Mellon University, an M.S in metallurgical engineering from Ohio State University, and a B.S. in engineering mechanics from the U.S. Air Force Academy.

Julie Chen is a professor of mechanical engineering and interim vice provost for research at the University of Massachusetts–Lowell (UML). She is one of three co-directors of the UML Nanomanufacturing Center of Excellence and is also co-director of the Advanced Composite Materials and Textile Research Laboratory. Before coming to UML, Dr. Chen was a program director for materials processing and nanomanufacturing at the National Science Foundation. She has served on the faculty of Boston University, has been a NASA-Langley Summer Faculty Fellow, has been a visiting researcher at two French universities, and has been an invited participant on three occasions in the National Academy of Engineering's Frontiers of Engineering Program. Dr. Chen has more than 20 years of experience in the mechanical behavior and deformation of fiber structures, fiber assemblies, and composite materials, with an emphasis on composites processing and nanomanufacturing. She serves on the editorial boards of the *Journal of Nanoparticle Research* and the *International Journal of Green Nanotechnology: Materials Science and Engineering*. Dr. Chen holds B.S., M.S., and Ph.D. degrees in mechanical engineering, all from the Massachusetts Institute of Technology.

David R. Clarke (NAE) is the Gordon McKay Professor of Materials and Applied Physics in the Harvard School of Engineering and Applied Sciences. He holds a B.Sc. degree in applied sciences from Sussex University in the United Kingdom and a Ph.D. in physics, as well as an Sc.D. degree from the University of Cambridge. Prior to moving to Harvard, he was a professor of materials at the University of California, Santa Barbara. Previous positions include senior manager, IBM Research Division; associate professor, Massachusetts Institute of Technology; group leader, Rockwell International Science Center; and senior scientific officer, the National Physical Laboratory (United Kingdom). Dr. Clarke has published more than 450 papers and holds five patents. He is a member of the National Academy of Engineering and a fellow of the American Physical Society, and he received an Alexander von Humboldt Foundation Senior Scientist Award. In addition, he is a Distinguished Life Member of the American Ceramic Society and was recently listed as author of one of the 11 best papers in the 110 years of publication of the *Journal of the American Ceramic Society*.

Bradford Cowles is an aerospace materials and structures consultant to both industry and government agency clients. Mr. Cowles has extensive experience in aerospace propulsion materials, specializing in materials behavior, materials-structure interactions, and life prediction. Mr. Cowles recently retired after 37 years at Pratt & Whitney, where his final position was senior fellow–Discipline Lead for Materials & Processes Engineering. This was the most senior technical position in a 325-person comprehensive materials engineering organization specializing in gas turbine engine materials and processes, including all phases of their development, characterization, and use in products. His responsibilities included oversight of technical projects and technology development programs, resolution of technical and product issues, and strategic planning for future technology and discipline development efforts. Mr. Cowles has extensive experience in titanium and nickel-based superalloys, including directionally solidified and single-crystal materials, as well as in advanced materials such as structural intermetallics. He has extensive expertise in the mechanics of materials, life prediction and damage tolerance methods, and experimental methods related to testing of materials and engine components. Recent focus areas include advanced surface treatments such as laser shock processing as well as materials and structures prognosis technology for gas turbine engines. In 2010, Mr. Cowles focused on developing materials-related strategic plans for a major aerospace company, consulting for aerospace companies on critical field issues involving materials and structures assessments, developing an actionable plan for integrated computational materials engineering (ICME), and using probabilistic methods for propulsion system validation for the U.S. Air Force. Mr. Cowles holds B.S. and M.S. degrees in engineering science from Florida State University and an M.S. degree in management from Rensselaer Polytechnic Institute.

George T. Gray III is a laboratory fellow and staff member in the dynamic properties and constitutive modeling team within the Materials Science Division of Los Alamos National Laboratory (LANL). He came to LANL following a 3-year visiting scholar position at the Technical University of Hamburg-Harburg (Germany) after having received his Ph.D. in materials science in 1981 from Carnegie Mellon University. As a staff member (1985-1987) and later team leader (1987-2003) in the LANL Dynamic Materials Properties and Constitutive Modeling Section within the Structure / Property Relations Group, he has directed a research team working on investigations of the dynamic response of materials. He conducts fundamental, applied, and focused programmatic research on materials and structures, in particular in response to high strain rate and shock deformation. His research is focused on experimental and modeling studies of substructure evolution and mechanical response of materials. These constitutive and damage models are used in engineering computer codes to support large-scale finite element modeling simulations of structures for applications ranging from national defense (DOE, DoD, DARPA), to industry (GM, Ford, Chrysler, and Bettis), to foreign object damage, to manufacturing. Dr. Gray is a Life Member of Clare Hall, Cambridge University, where he was on sabbatical in the summer of 1998. He is currently the president of the Minerals, Metals, and Materials Society (TMS); is a fellow of the American Physical Society and of ASM International; and serves on the International Scientific Advisory Board of the European DYMAT Association. He also serves on the board of governors for *Acta Materialia*. Dr. Gray is a member of the NRC National Materials Advisory Board.

Eric Greene is a naval architect and marine engineer who focuses on marine composites. He has lectured nationally and internationally on the topic and is the author of the highly acclaimed book *Marine Composites*. In 1988, he founded Eric Greene Associates, Inc., with the goal of advancing the understanding of composite materials for marine structures. The company focuses on large composite structures for naval, commercial, and recreational applications, allowing for technology transfer among diverse industries. Its research and development also covers non-destructive evaluation (NDE), repair, and wave impact. The company's recent projects include technology transfer assistance for a major Norwegian shipbuilder supporting the U.S. Office of Naval Research (ONR); cost modeling of a next-generation Navy hovercraft for the ONR ManTech program; development of a "stowable" megayacht helicopter landing platform; calculation of riser loads for a floating transit offloading and storage platform; revision of NAVSEA Technical Publication T9074-AX-GIB-010/100, "Material Selection Requirements," to include updated guidelines for composites; and development of the Technology Road Map for Shipboard Naval Composites for the ONR ManTech program. Mr. Green holds a B.S. in naval architecture and marine engineering from the Massachusetts Institute of Technology.

Wesley L. Harris (NAE) is the Charles Stark Draper Professor and head of the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology. His research focuses on theoretical and experimental unsteady aerodynamics and aeroacoustics, computational fluid dynamics, and the government policy impact on procurement of high-technology systems. Prior to this position he served as the associate administrator for aeronautics at NASA. He has also served as the vice president and chief administrative officer of the University of Tennessee Space Institute. Dr. Harris has served on committees of the American Institute of Aeronautics and Astronautics (AIAA), the American Helicopter Society (AHS), and the National Technical Association (NTA) and has been an advisor to eight colleges, universities, and institutes. He was elected a fellow of the AIAA and of the AHS for personal engineering achievements, engineering education, management, and advancing cultural diversity. Dr. Harris has served as chair and member of various boards and committees of the National Research Council (NRC), the National Science Foundation (NSF), the U.S. Army Science Board, and several state governments. He holds a B.S. in aerospace engineering from the University of Virginia and M.S. and Ph.D. degrees in aerospace and mechanical sciences from Princeton University.

Manish Mehta has been director of collaboration programs at the National Center for Manufacturing Sciences (NCMS) since 2001. He is also executive director of Technologies Research Corporation, a subsidiary of NCMS, established to provide professional technology management services for new technologies and alliances. His responsibilities include assessing emerging manufacturing-related technology needs in the national interest and developing collaborative research and development projects with NCMS's defense, industrial, and academic members. These collaborations include projects in fuel cell component manufacturing, lightweight materials, and nanomanufacturing technologies. He previously served as director of the Aluminum Metal Matrix Composites Consortium (a supplier group hosted by NCMS) and was the convener of the Steel Joint Industry Alliance of steel-making, forging, heat-treating, powder metal, and end-user industries and trade organizations, formed to promote greater cross-industry leveraging in research. He also served as Peer Review Agency director of the 2008 Michigan 21st Century Jobs Fund Business Plan Competition. Dr. Mehta is a former member of the NRC's Board on Manufacturing and Engineering Design.

Gregory B. Olson (NAE) is the Walter P. Murphy Professor of Materials Science and Engineering at Northwestern University, where he directs the Materials Technology Laboratory/Steel Research Group at the McCormick School of Engineering and Applied Science. He was elected to the National Academy of Engineering in 2010 for his contribution to research, development, implementation, and teaching of science-based materials by design. Dr. Olson is considered one of the founders of computational materials design. He developed a systematic science-based approach for designing alloys that takes the desired properties and calculates the optimum composition and processing route. In 1997, he founded QuesTek Innovations LLC, a materials design company. Dr. Olson is a fellow of ASM and of the Minerals, Metals and Materials Society (TMS). He received B.S., M.S., and Ph.D. degrees in materials science from the Massachusetts Institute of Technology and remained there in a series of senior research positions before joining the faculty of Northwestern University in 1988. Beyond materials design, his research interests include phase transformations, structure/property relationships, and applications of high-resolution microanalysis. Recent awards include the ASM Campbell Memorial Lectureship, the TMS-SMD Distinguished Scientist/Engineer Award, and the Cambridge University Kelly Lectureship.

Charles Saff is chief engineer for structural certification and qualification for Boeing Research and Technology. In addition to his Boeing responsibilities, Mr. Saff leads a multi-national working group for NATO-RTO on the development of guidelines for structural design and qualification of unmanned military aircraft. He also serves on the U.S. Air Force Scientific Advisory Board. He has led multicompany programs in technology development and transition for DARPA/USAF (X-45A and Composites Affordability Initiative), DARPA/Navy (Accelerated Insertion of Materials program), and NASA (High Speed Research program). He has performed full-scale test reviews for the Boeing 787, structural integration for the X-45A Prototype UCAV, and structural qualification for the YF-23 aircraft. Mr. Saff has performed more than 50 research and development projects in strength and fatigue of metallic, composite, metal matrix composite, and hybrid materials and structures over his career at McDonnell Douglas and Boeing. He served on the NRC Committee on Aging of Air Force Aircraft in 1996-1997 and has also served on several review committees for U.S. Air Force and NASA internal research and development. Mr. Saff has been active for many years in both the American Institute of Aeronautics and Astronautics (AIAA) and the American Society for Testing and Materials (ASTM), serving as committee member, committee chair, and international conference chair for ASTM. For AIAA, Mr. Saff has served nationally as deputy director, director, and vice president of technical activities. He is currently a member of the Ethics Committee for the board of directors of AIAA. Mr. Saff is an AIAA fellow and a Boeing technical fellow.

Darrell R. Tenney is retired from the NASA Langley Research Center, where he was chief of the Materials Division and former director of the Airframe Systems Program. Dr. Tenney has extensive experience and expertise in researching and developing advanced composites and metallic materials; in applying advanced composites to aerospace structures for both aircraft and spacecraft; in determining the environmental effects on materials in both aircraft and space applications; in conducting technology assessments; in identifying critical barriers and developing solutions to them; in identifying key challenges for developing new R&D efforts; and in formulating and advocating for new programs. He has conducted numerous technology assessments, including assessments of the R&D programs under European Frameworks V and VI and assessments of European efforts to build composite primary structures for the Airbus family of aircraft. He was the lead on the study "Evaluation of Advanced Composite Structure Technologies for Application to NASA's Vision for Space Exploration," conducted by AS&M, Inc., for NASA Langley.

Francis W. Zok is a professor and associate chair of the Materials Department at the University of California, Santa Barbara. His research over the past 20 years has addressed the thermal and mechanical properties of multiphase materials and structures. His recent activities have focused on three specific areas. The first involves protection systems for military ground vehicles, principally against improvised explosive devices. The second focuses on personnel protection systems. The third is on high-temperature ceramic composites for use in future propulsion systems in military and civilian aircraft as well as hypersonic flight vehicles. Dr. Zok has been an associate editor of the *Journal of the American Ceramic Society* since 1993. He has served on the editorial board for *Current Opinion in Solid State and Materials Science;* the Scientific Advisory Board for the AFRL Materials and Manufacturing Directorate; the National Academies Technical Assessment Board for the ARL Panels on Air and Ground Vehicle Technology and on Armor and Armaments; the National Science Foundation Panel on Nanomechanics; and the Expert Review Committee on Materials Science, Canada Foundation for Innovation. He is currently chair of the Scientific Advisory Board for the Canadian Magnesium Network. Dr. Zok is the author of five book chapters and more than 150 scientific publications.

Appendix B

Presentations to the Committee

MEETING 1

July 20-21, 2010
The Keck Center of the National Academies
Washington, D.C.

Background Information and Study Goals
Julie Christodoulou, Director, Naval Materials Division, Office of Naval Research

Overview: Reliance 21 Community of Interest—Materials & Processes
Robert Rapson, Chief Engineer, Materials and Manufacturing Directorate, Air Force Research Laboratory

Use of Composite Materials for Weight Reduction in Navy Applications
Gene Camponeschi, U.S. Navy, Carderock Division, Structures and Composites

Application of Lightweighting for Naval Ships—A Structural Metals Perspective
John Deloach, Structural Metals and Processing, Office of Naval Research

Lightweighting Strategies for Army Ground Combat Systems
Suveen Mathaudhu, U.S. Army Research Laboratory, Weapons and Materials Research Directorate

MEETING 2

September 20-21, 2010
The Keck Center of the National Academies
Washington, D.C.

Lightweight Aluminum Structure for Ships and Craft
Robert A. Sielski, Consulting Naval Architect—Structures (retired, Naval Sea Systems Command)

Ground Systems Integration Domain (GSID) Materials for Ground Platforms
Lisa Prokurat Franks, U.S. Army, Tank and Automotive Research, Development and Engineering Center (TARDEC), Research, Development and Engineering Command (RDECOM)

Transparent Materials for Armor—A Cost Study
Lisa Prokurat Franks, U.S. Army, Tank and Automotive Research, Development and Engineering Center (TARDEC), Research, Development and Engineering Command (RDECOM)

Materials and Process Engineering Lightweight Initiative
Robert Hathaway, Vice President, Oshkosh Corporation

Lightweight Materials for Air Force Applications: "There's No Free Ride"
James Malas, Technical Advisor, Partnering Division, Air Force Research Laboratory, and Robert Rapson, Chief Engineer, Materials and Manufacturing Directorate, Air Force Research Laboratory

Briefing to the NMAB: Benchmarking the Technology and Application of Lightweighting
Charles Kuehmann, President and Chief Executive Officer, QuesTek Innovations

MEETING 3

October 28-29, 2010
The Keck Center of the National Academies
Washington, D.C.

Lightweight Technologies: An Automotive Industry Experience
Bruno Barthelemy, Chief Engineer, Body Structures/Closures, Ford Motor Company

Jim Ogonowski, Vice President for Engineering—Airplane Structures, Boeing Commercial Airplanes (via teleconference)

MEETING 4

December 8, 2010
Internet Presentation and Teleconference

Lightweighting in Military Vehicles
BAE Systems, Land and Armaments, U.S. Combat Systems

Roger Halle, Survivability Capabilities Manager, Systems Engineering Manager for Technology Development

Mark Middione, Technology Team Manager—Survivability

John Gill, System Engineering Technology Team Lead

Appendix C

Acronyms and Abbreviations

AAV	amphibious assault vehicle
ACAV	armored cavalry assault vehicle
AEM/S	Advanced Enclosed Mast/Sensor
AFOSR	U.S. Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AGATE	Advanced General Aviation Transport Experiments
AIM	accelerated insertion of materials
AMPTIAC	Advanced Materials and Process Technology Information Analysis Center
AP	armor piercing
APC	armored personnel carrier
ARVN	Army of the Republic of Vietnam
ATD	advanced technology demonstration
CBM	condition-based maintenance
CCM	composite crew module
CTE	coefficient of thermal expansion
DARPA	Defense Advanced Research Projects Agency
DoD	U.S. Department of Defense
EFP	explosively formed projectile
EFV	expeditionary fighting vehicle
EME	electromagnetic environment/effects
FCS	Future Combat System
FSW	friction stir welding
GAO	U.S. Government Accountability Office

HMMWV	High-Mobility Multipurpose Wheeled Vehicle
HSLA	high-strength, low-alloy
ICME	integrated computational materials engineering
IDF	Israeli Defense Force
IED	improvised explosive device
JHSV	joint high-speed vessel
JLOTS	joint logistics over the shore
JLTV	joint light tactical vehicle
LASS	lightweight construction applications at sea
LCAC	landing craft, air cushion
LCS	littoral combat ship
LCU	landing craft, utility
LSV	logistic support vessel
ManTech	U.S. Department of Defense Manufacturing Technology Program
MMC	metal matrix composite
MRL	manufacturing readiness level
NDE	non-destructive evaluation
NRC	National Research Council
NSTC	National Science and Technology Council
O&S	operations and support
ONR	U.S. Office of Naval Research
RDT&E	research, development, test, and evaluation
RPA	remotely piloted aircraft
RPG	rocket-propelled grenade
S&T	science and technology
SES	surface effect ship
SLWT	super-lightweight tank
SOC	special operations craft
SSC	ship-to-shore connector
TARDEC	Tank Automotive Research, Development & Engineering Center
TMS	Minerals, Metals & Materials Society
TRL	technology readiness level
UAV	unmanned aerial vehicle
VARTM	vacuum-assisted resin transfer molding