ACCELERATING TECHNOLOGY TRANSITION
Bridging the Valley of Death for Materials and Processes in Defense Systems

Committee on Accelerating Technology Transition
National Materials Advisory Board
Board on Manufacturing and Engineering Design
Division on Engineering and Physical Sciences

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Preface

Faster incorporation of new technologies into complex products and systems holds the possibility of ever-increasing advantages in cost, performance, durability, and new functionalities. A general perception on the part of many investigators is that incorporation of change is more difficult, expensive, and slow than it need be. The management of change in complex products and systems, however, does require an understanding of the significance of those changes as well as their consequences in terms of product performance and safety. Many lessons learned in practice have at their root the common theme that such understanding was not apparent at the time of commitment to and introduction of change. Thus certain industry segments such as aerospace have developed cultural beliefs that in part are focused on constraining change until significant evidence based on empirical use indicates that unintended consequences will not occur. The two sets of perceptions—the desire for timely incorporation of change, and caution in the face of its possible effects—create a significant tension between those charged with the development of new technology capabilities and those who feel accountable for the consequences of such technology incorporation.

In November 2003, in response to a request from the Defense Science and Technology Reliance Panel for Materials and Processes of the Department of Defense (DoD), the National Research Council held a workshop to address how to accelerate technology transition into military systems. The workshop centered on the need to better understand interactions between the various stakeholders in this process of the incorporation of technological change. The examples used and the focus of the workshop involved issues related to materials and processes for unclassified programs, although the hope is that learning gained from the workshop will be applicable to other technical domains of DoD programs.

The Committee on Accelerating Technology Transition, which organized and conducted the workshop, was asked to examine the lessons learned from rapid technology applications by successful, integrated design/manufacturing groups and to carry out the following tasks:

- Examine how new high-risk materials and production technologies are quickly adopted by successful integrated design/manufacturing groups. These groups include those in aerospace (such as Boeing's Phantom Works and Lockheed Martin's Skunk Works) and racing sport industries (such as America's Cup sailboats);
- Develop the lessons learned from these materials and production technology applications including computational research and development, design and validation methodologies, collaborative tools, and others;
- Identify approaches and candidate tool sets that could accelerate the use of new materials and production technologies in defense systems—both for the case of future systems and for improvements to deployed systems; and
- Prepare a report.

Through biweekly teleconferences and e-mail correspondence, the committee (Appendix A contains biographical sketches of its members) embraced this charge. It devised a program, located speakers, and developed a workshop agenda (contained in Appendix B). The committee organized the workshop into technical sessions to evaluate the range of issues involved in accelerating technology transition and to consider a wide range of perspectives, including such nontraditional aspects as racing cars, America's Cup yachts, and biomedical applications. The sessions were as follows:

- Technology Transition Overviews
- Integrated Design/Manufacturing Groups—Case Studies
- Computational and Collaborative Tools—Lessons Learned
- Design and Validation Methodologies—Lessons Learned
- Approaches/Tools for Accelerated Technology Transition
- Lessons Learned from Other Industries

A seventh session was held at the end of the workshop to summarize the observations and receive additional comments from the workshop attendees.

Through these sessions, the committee received a wide range of information and observations that, taken together, shed light on three key issues—people/culture, processes, and tools—as described in the report. While the general topic of accelerating technology transition has been studied in some depth in the literature, this workshop brought into focus a unique combination of personal perspectives, technical tools, business processes, and a context in which to view them. Intended to identify ways to enhance and thus speed up the process of incorporating technological change, the report is organized as follows: after the Executive Summary, Chapter 1 discusses the culture for innovation and rapid technology transition, Chapter 2 discusses the methodologies and approaches for rapid technology transition, and Chapter 3 identifies the enabling tools and databases available for rapid technology transition as well as a need for further development in these areas. The report includes information gathered from the workshop as well as from the literature. The recommendations presented are based on committee deliberations on the themes emerging from the workshop.

The committee acknowledges the outstanding support of the National Research Council staff and, in particular, the leadership and professional assistance provided by Arul Mozhi. The committee also acknowledges the speakers and those who served as liaisons to the DoD, who took the time to share their ideas and experiences with us during the very busy travel period of the shortened workweek of Thanksgiving. These liaisons were Julie Christodoulou, Office of Naval Research; William Coblenz, Defense Advanced Research Projects Agency; Bruce K. Fink, U.S. Army Research Laboratory; and Mary Ann Phillips, U.S. Air Force Research Laboratory.

Lastly, I would like to acknowledge the outstanding work performed by the committee members, all of whom deserve accolades not only for the tasks accomplished but also for the incredibly quick turn-around time of their efforts, allowing the committee to organize and execute the work statement in such a short period of time.

This report has been 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. We wish to thank the following individuals for their review of this report: John Allison, Ford Motor Company; Robert M. Hathaway, Oshkosh Truck Corporation; Glenn Havskjold, Boeing Rocketdyne; Elizabeth Holm, Sandia National Laboratories; Mark H. Kryder, Seagate Technologies; Ronald K. Leonard, Deere and Company; Cherry A. Murray, Lucent Technologies; Maxine L. Savitz, Honeywell, Inc.; John J. Schirra, Pratt & Whitney; and Joe Tippens, Universal Chemical Technologies, Inc.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by George Dieter, University of Maryland. 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 the institution.

The following individuals also greatly assisted the work of the committee through their participation in many of the committee's activities as liaisons from the National Research Council boards that initiated the study: James Mattice, Universal Technology Corporation, from the Board on Manufacturing and Engineering Design; and Alan G. Miller, Boeing Commercial Airplane Group, from the National Materials Advisory Board.

Diran Apelian, *Chair*
Committee on Accelerating Technology Transition

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Executive Summary

The Department of Defense (DoD) is in the process of transforming the U.S. armed forces from a Cold War-era fighting force to one that is lighter, more flexible, and more reliant on technology. This fighting force will be able to respond to a wide range of asymmetric threats with speed and efficiency. Accelerating the transition of new technologies into defense systems will be crucial to achieving this military transformation. However, the typical time required for moving new materials and processing technologies from research to applications is at least 10 years, and many times even longer. Historical precedents for the transition of new technologies into defense systems have been neither fast nor efficient.

These typically long delays are attributed to the complexity of the invention, development, and transition process. Technology transition involves a variety of internal and external partnerships for the various stages of the process. Usually, academic, government, and industrial corporate laboratories lead the concept refinement and technology development; industry leads system development, demonstration, and production; and warfighters take the lead in deployment, operations, and support. While each partner has a critical responsibility in the process, team members may all have different goals, time lines, and funding levels. Achieving active collaboration among these partners during all phases of technology transition is a key goal for success.

Recognizing these challenges, the DoD is exploring methods to expedite the adoption of new materials technologies in defense systems. To increase understanding in this area, the DoD requested that the National Research Council (NRC) sponsor a focused workshop to examine the lessons learned from rapid technology applications by successful, integrated design and manufacturing groups. The NRC Committee on Accelerating Technology Transition was formed to carry out this task. The committee carried out a number of information-gathering and deliberative activities, including holding an interactive workshop in November 2003 on accelerating technology transition. On the basis of this work, which included directed discussions at the workshop, a number of virtual meetings, and a thorough review of existing literature in the field, three specific areas emerged, as follows:

- Creating a culture for innovation and rapid technology transition,
- Methodologies and approaches, and
- Enabling tools and databases.

CREATING A CULTURE FOR INNOVATION AND RAPID TECHNOLOGY TRANSITION

Accelerating the technology transition of new materials and processes is a challenging, long-term endeavor that begins at the conceptual stage of a new material or technology and continues through its implementation and acceptance. The essence of this lengthy process is communication. Workshop participants consistently described successful technology transition as a long-term dialogue between the creators and the end users of new technologies. Materials and processing technologies present a particular challenge to effective communication, because materials in and of themselves are rarely products that can be directly linked to defense needs. To foster communication, prototypes of components need to be put into the hands of potential customers as early as possible in order to gain them as advocates for the technology. This type of buy-in is essential. An additional and essential factor is a champion with sufficient authority to remove barriers, garner support, and ensure a new technology's successful implementation and use.

Effective technology transition, involving collaboration among all of these stakeholders, drives an iterative process of development, implementation, and acceptance. Both the technical team and the product users must be part of the end-to-end decision-making process. The successful transition of new technologies depends on the ability of managers to focus on technologies that can be matched to compelling needs. Managers must also work with potential customers to develop an adequate business case. Successfully managing this complex collaborative interaction requires leaders who understand and respect the values, working styles, and goals of different groups and who can also effectively initiate and sustain communication among the stakeholders across all organizational and institutional boundaries.

A central theme of the workshop was the importance of creating a culture that fosters innovation, rapid development, and accelerated technology transition. Success stories from many industry sectors—commercial, sports, and defense—point to similar key elements of such a culture. These elements include flexibility, a willingness to take risks, open communication without regard to hierarchy, a sense of responsibility that replaces unquestioned authority, and a commitment to success that goes beyond functional roles. Creating such a culture has several fundamental implications: individuals must feel empowered to take risks, management must anticipate and plan for failure, and everyone must champion teamwork and collaboration over individual accomplishments. Engineers and scientists responsible for innovation and development must be allowed to experiment, to think freely, and to fail on occasion. To encourage innovation, the dictum that failure is not an option is replaced by the understanding that failure provides lessons learned in an innovative environment.

In an establishment as large and complex as the U.S. military, the adoption and acceptance of a new technology likely depend on the real or perceived impact of that technology on high-level military goals. A particular challenge for the military in trying to accelerate the use of new materials is the challenge of overcoming cultural traits that are associated with hierarchical and rule-bound organizations and that impede technology transition. For example, such a culture may favor traditional defense contractors over smaller companies and start-up enterprises.

In general, an operations infrastructure must be flexible enough to meet the demands of highly collaborative, fast-paced, high-risk projects, and it must be able to accommodate change during the development process. Changing a hierarchical culture may mean decentralizing decision making, simplifying procurement and acquisition processes, reducing budget lead times, providing consistent funding through technology development and maturation, making greater use of off-the-shelf technology, and valuing innovation over short-term economic efficiency. This changing paradigm may also necessitate updating standards and testing procedures to make it easier to introduce new materials.

The potential rewards of making such a cultural change are substantial. Materials have the unique ability to contribute to a wide range of technical objectives, such as increased mobility and survivability, while offering significant capital, operating, and maintenance cost savings. Although initial costs may be higher for an accelerated development path, an overall cost savings and a faster return on investment may be realized. Perhaps even more compelling is that by better matching the development and deployment time frames in the venture-capital industry, the military can leverage dual-use, commercial development and billions of dollars in private equity capital.

The committee finds that there is no single strategy that, if implemented, will accelerate the insertion of new technologies into either commercial or military systems. Instead, it is more likely that the omission of a key element of the many needed will guarantee failure. Having a strong organizational culture and structure in place is a necessary but not sufficient condition for the successful acceleration of technology transition. Some common characteristics of successful technology transition efforts include the following:

- *The establishment of Skunk Works-like enterprises*—these groups are committed, multidisciplinary teams led by champions who inspire and motivate their teams toward specific goals;
- *Team determination to make the technology succeed*—which may include making the technology profitable and demonstrating to customers that they need the technology;
- *The use of expanded mechanisms of open and free communication*—especially involving the ability to communicate an awareness of problems that will affect process goals; and
- *The willingness of the champion to take personal risk*—such leadership results in the willingness of the organization to take risks at the enterprise level.

Recommendation 1. The Department of Defense (DoD) should endeavor to create a culture that fosters innovation, rapid development, and the accelerated deployment of materials technologies.

Success stories from commercial, sports, and defense industries suggest that the characteristics of such a culture include the following:

- Acceptance of risk, anticipation of failure, and plans for alternatives;
- A flexible environment with the ability to accommodate change during the development process;
- Open communication in all directions without regard to hierarchy;
- A widespread sense of responsibility and commitment to success that exceed defined functional roles;
- Valuing of innovation over short-term economic efficiency; and
- A passionate focus on the end-user's needs.

Evaluating and implementing the following actions will enable the DoD to create a culture that fosters rapid development and breaks down barriers to rapid technology transition:

- Introduce flexibility that reduces budget lead times and provides consistent funding during the technology development stage through full maturity,
- Make better use of commercial off-the-shelf technology,
- Implement shorter and more iterative design and manufacturing processes,
- Simplify procurement and acquisition processes,
- Update standards and testing procedures to make it easier to introduce new materials and processes, and
- Decentralize decision making throughout the process.

Leveraging private equity capital and pursuing dual-use commercial development can also be effective. Investments in materials processes and technology will offer the DoD the opportunity to leverage materials technology for defense systems across all service branches.

METHODOLOGIES AND APPROACHES

Most of the best practices discussed at the Workshop on Accelerating Technology Transition function by altering the risk–reward relationship of the military customer and its suppliers. The primary method of doing so is to work to the desired technology function rather than to predetermined specifications. This can be accomplished by better quantifying the rewards associated with success and by mitigating the risk of failure. The risk–reward relationship for failure or success in military systems was noted as a primary barrier to the insertion of new technologies into military systems.

While several corporate best practices are effective at accelerating technology development and product introduction into the public marketplace, certain identified best practices increased the chances of success and lowered the perceived risk of failure. Risk includes not only personal risk but also technical and business risk. The committee identified three corporate best practices that are effective at modifying the risk–reward balance and thereby accelerating technology development and product introduction into the commercial marketplace.

Best Practice 1: Developing a Viral Process for Technology Development

One of the successful best practices identified by the committee is that of developing a "viral" process for technology development.[1] This process entails quick, iterative development cycles and prototyping of materials and products. The development cycles and prototyping processes must be done in parallel and also in close consultation, if not actual collaboration, with potential customers. One of the primary reasons for successful rapid development in industry is the use of multidisciplinary teams that keep the development going without getting bogged down in any one of its aspects. The key to rapid technology development is to virally incorporate knowledge into the development process and to modify the materials, fabrication processes, and systems as needed. Agile manufacturing processes[2] are needed for all stages in materials development—from research to prototyping and pilot production, to full-scale production.

Effective modeling of materials and processes is a critical part of viral development. To accelerate the initial selection of materials, combinatorial and other high-throughput materials research methods show great promise in developing the materials property data needed as input for purposes of differentiating competing materials and processes. Many engineers at the workshop observed that once the selected materials are inserted into fabrication processes, the perceived risk of failure, particularly for critical components, increases with time as complexities are revealed and the demands on technology increase. As components become larger and more complex, two or more iterations are sometimes required before making a finished part. The only effective way to accelerate this process is to use predictive models to redesign fabrication processes. Many modeling tools already exist, but more are needed. A comprehensive suite of materials modeling software and verified data could accelerate the development and insertion of appropriate materials into critical systems.

A tool that is strikingly effective in aiding the insertion of high-performance, multifunctional materials in America's Cup sailboats and Formula 1 racing cars is system-level software that quantifies how system performance changes with the insertion of new materials in new designs. Such modeling in DoD systems could aid in setting priorities for the development of new materials. These models must reflect the economics of the materials and processes. Traditional cost-accounting models do not utilize

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[1] "Viral" is used in this context to mean that the process is infectious and self-propagating. A process that meets this criterion provides 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.

[2] "Agile" implies a well-controlled manufacturing process. Process-control strategies that meet this goal include six-sigma and disciplined design-of-experiments concepts.

all of these factors. An understanding of the relevant economic factors can help researchers and system developers optimize manufacturing conditions and evaluate the performance of the materials and fabrication systems that seem most economically viable. This optimization of technical performance and economic performance is vital for the successful insertion of new materials.

Best Practice 2: Increased Reliance on Functional Requirements Rather Than on Specifications

A second successful best practice identified by the committee is that of increasing reliance on functional requirements rather than on specifications. One of the key limitations to the rapid insertion or development of new technology, particularly for the DoD, is the lack of information given to vendors about the relevant functional and technological needs. Instead, strict adherence to detailed but incomplete specifications is expected. The benefits of a functionality approach can be seen in the contrasting business models for Formula 1 race teams and the military aerospace market. Using the team-based approach with parallel development and constant iteration of design cycles, a new product for the Formula 1 market could be produced, tested, and certified for use in approximately 8 months from initial development to volume production. This time frame is in stark contrast to the dramatically longer period for the military aerospace market, even though the systems and components are remarkably similar. The key observed difference is the level of risk that the two industries are willing to take; this level of risk acceptance influences every aspect of the enterprise.

Military specifications have been essential for purposes of certifying that a particular material or system will have an extremely low probability of failure in use. However, for the development of new technologies, specifications reduce the ability to rapidly implement existing knowledge and technologies developed for nonmilitary systems by the different vendors. Having an understanding of the desired functionality, including the fabrication envelope and the use environment, would significantly accelerate finding the right material and the right technology solution, thereby accelerating technology transition. The increased reliance on functionality rather than on specifications can be implemented only by having all stakeholders involved and sharing information.

Best Practice 3: Developing a Mechanism for Creating Successful Teams

A third successful best practice identified by the committee is that of developing a mechanism for creating successful teams in a sustainable way. The creation of such teams must be independent of the industry and sector, as new products are envisioned. The success of committed, multidisciplinary teams that implement iterative prototyping and work to function rather than to specification was brought up with respect to many different industries and in many different forms throughout the workshop. As these teams operate, if an issue is discovered in the manufacturing processing of a material, this information would then rapidly be transferred to other materials-development processes as well as to the testing and verification processes. Likewise, the solution to an issue that has arisen could emerge from this process. The industry speaks of this overall process as a constant adjustment of tasks through viral cross-functional interaction.

The committee finds that technology incubators are a useful construct for accelerating technology transition. The concept of people having the right technologies, the right team skills, and the right financial support is not new; additionally, all successful transitions need to have the customers as part of the team from the beginning in order to ensure meeting the military's high performance requirements. The challenge in the case of accelerating technology transition in military systems is that the roles in such an enterprise will be distinctly different from those in the venture-capital world, because the military may be filling all of the roles—i.e., as the venture capitalist, the technology developer, and the customer. Within the military, there may still be conflicting goals, such as minimizing both initial and life-cycle costs.

The creation, management, and interaction of such multidisciplinary teams with the DoD cannot be ad hoc and must be supported at the highest levels, or the teams will likely be unsuccessful.

Adoption of Best Practices

Methods for encouraging movement toward the best practices described above are not obvious. Assessing the performance of any technology transition scheme must be organized such that investments in more successful strategies can be more frequently realized. Methods for assessment must also provide some measure of accountability within the responsible organization, in both industry and government. When performance indicators are used to assess success, the time duration for technology transition from conception to implementation is likely to decrease. It is not clear that implementation of these best practices can overcome what is called the gap between technological invention and acquisition, also known as the valley of death. A number of changes will be needed, including streamlining military acquisition, to allow all of these changes to be implemented.

These three best practices were identified as being critical to such streamlining. While other corporate best practices are also effective at accelerating technology development and product introduction into the commercial marketplace, these three have been shown to increase the chances of success and to lower the perceived risk of failure, including personal, technical, and business risk.

Recommendation 2. The Department of Defense should adopt the following three best practices found in industry for the accelerated transition of new materials and technologies from concept to implementation.

- **Develop a viral process, one that is infectious and self-propagating, for technology development through the quick, iterative prototyping of materials and products, with free and open communication; agile manufacturing processes; and effective modeling of materials, processes, system performance, and cost;**
- **Work to functional requirements rather than to specifications; and**
- **Develop a flexible mechanism for creating and recreating successful teams as new systems are envisioned.**

ENABLING TOOLS AND DATABASES

The well-established success of computational engineering in various disciplines has fostered a rapid adaptation of computation-based methods to materials development in the commercial sector in recent years. Early successes in computational materials engineering provide a clear vision of a path forward to enhance capabilities across national academic, industrial, and government pursuits.[3,4]

The first demonstrations of computation-based methods for materials development integrated empirical materials models. A new level of capability has been demonstrated very recently in the development and application of more predictive mechanistic numerical models. These capabilities have been nurtured under such federally funded initiatives as the Defense Advanced Research Projects Agency (DARPA) program on Accelerated Insertion of Materials (AIM) and the Air Force program on Materials Engineering for Affordable New Systems (MEANS). Demonstrated abilities include (1) accelerated process optimization at the component level; (2) reducing risk associated with scale-up; (3)

[3] National Research Council. 2003. Materials Research to Meet 21st Century Defense Needs. Washington, D.C.: The National Academies Press, pp. 3-4.
[4] National Research Council. 2004. Retooling Manufacturing: Bridging Design, Materials, and Production. Washington, D.C.: The National Academies Press.

efficient accurate forecasting of property variation to support qualification, with reduced testing, for early adoption; and (4) the active linking of materials models to broader process and property trade-offs in the higher-level system design process, all for the optimal exploitation of new materials capabilities.

Current projects are actively applying the new tools and new approach in the accelerated implementation of materials and processes in both polymer-matrix composites and metallic alloys for aerospace applications. Small businesses have played a vital role in these collaborative efforts, providing databases, tools, and methods, and expanding capabilities to include the initial parametric design of "designer materials," uniquely offering a new level of predictability ideally suited to the accelerated development and qualification process.

Principal challenges and opportunities for the advancement of these capabilities are in the following areas: (1) the wider dissemination of information on current capabilities and achievements; (2) the rapid transformation of the current array of academic computational materials-science capabilities into useful engineering tools; (3) the broader development of necessary fundamental databases; and (4) a major infusion of modern design culture into our academic institutions to provide a pertinent research and education environment.

Recommendation 3. The Office of Science and Technology Policy should lead a national, multiagency initiative in computational materials engineering to address three broad areas: methods and tools, databases, and dissemination and infrastructure.

- *Methods and tools.* A collaboration between academia and industry built on such models as the Accelerated Insertion of Materials (AIM) program of the Defense Advanced Research Projects Agency should focus on the rapid transformation of existing, fundamental materials numerical modeling capabilities into purposeful engineering tools on a pre-competitive basis. The scope of the effort should encompass all classes of materials and the full range of materials design, development, qualification, and life cycle, while integrating economic analysis with materials- and process-selection systems.
- *Databases.* An initiative should focus on building the broad, fundamental databases necessary to support mechanistic numerical modeling of materials processing, structure, and properties. Such databases should span all classes of materials and should present the data in a standardized format. New, fundamental database assessment protocols should explore optimal combinations of efficient experimentation and reliable first-principles calculations.
- *Dissemination and infrastructure.* A dissemination initiative should provide ready access to a Web-based source of pre-competitive databases and freeware tools as well as accurate information on the range of existing, commercial software products and services. Integrated product team-based research collaborations should be deliberately structured so as to firmly establish a modern design culture in academic institutions to provide the necessary, pertinent, research and education environment.

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Creating a Culture for Innovation and Rapid Technology Transition

The concept of the "valley of death" has become an icon for the difficulty of successfully commercializing or implementing proven technologies.

WHAT IS TECHNOLOGY TRANSITION AND WHY IS IT DIFFICULT?

In his book *Diffusion of Innovation,* Everett M. Rogers poses the question "What is so difficult about technology transfer?" and concludes that "technology transfer is difficult, in part, because we have underestimated just how much effort is required for such transfer to occur effectively."[1] Rogers defines technology transfer as a communication process:

> The conventional conception of technology transfer is that it is a process through which the results of basic and applied research are put into use by receptors. This viewpoint implies that technology transfer is a one-way process, usually from university-connected basic researchers to individuals in private companies who develop and commercialize a technological innovation. . . . Most scholars realize that technology transfer is really a two-way exchange. Even when technology moves mainly in one direction, such as from a university or a federal R&D lab to a private company, the two or more parties participate in a series of communication exchanges as they seek to establish a mutual understanding about the meaning of the technology. Problems flow from potential users to researchers, and technological innovations flow to users, who ask many questions about them. Thus technology transfer is usually a two-way, back-and-forth process of communication.[2]

Embodied in this definition of technology transfer is the importance of a long-term partnership between the creators and the end users of the new technology. This partnership drives an iterative process of development, implementation, and acceptance. The view of technology transfer as a collaborative process among stakeholders is consistent with presentations made at the November 2003 Workshop on Accelerating Technology Transition by speakers from industry, academia, and the defense sector (the agenda of the workshop is presented in Appendix B). Many ongoing programs are designed to facilitate technology transition to the defense sector and there are many success stories. The particular challenge addressed here is the rapid transition of new materials. Because materials in and of themselves are rarely products that can be directly linked to defense needs, the need for continuous communication between developers and users is especially critical. This chapter addresses the

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[1] E.M. Rogers. 2003. Diffusion of Innovation, 5th ed. New York, N.Y.: Free Press, p. 152.
[2] Rogers, 2003. See note 1 above, p. 150.

challenges of creating a culture that fosters innovation and rapid technology transition. As discussed in the following sections, success stories suggest that, in addition to the participation of all stakeholders, characteristics of such a culture include flexibility, a willingness to take risks, cross-communication, and the existence of champions.

THE CULTURE OF INNOVATION AND RAPID TECHNOLOGY TRANSITION

Experience in industry and research in the fields of history of technology, business, and social studies of science point to ways in which institutional, social, cultural, and historical factors influence the adoption, implementation, and long-term acceptance of new technology. Even though there is a large body of literature from these fields, exploring and understanding the adoption of technology from this perspective are often overlooked, or ignored as being too complex to consider. For scientists and engineers, there is a tendency to see only technological solutions for failures in technology transition—the problem is formulated as one of first measuring and quantifying properties, and then of demonstrating performance, manufacturability, and cost-effectiveness. The remaining problem is one of communication, for which scientists and engineers may also see technological solutions (virtual reality, information visualization, Internet meetings, and so on).

This approach overlooks the fact that the introduction and acceptance of new technology often depend more on social, cultural, and historical factors than on technological merit. And technological merit itself is subjectively defined, even if properties can be measured and quantified. As discussed in detail in the following sections, fascinating historical examples demonstrate how social and cultural factors influence the development, implementation, and use of new technologies. Just recently, the independent committee investigating the disaster involving the space shuttle *Columbia* highlighted the importance of institutional culture in its findings, pointing to the self-protective culture of the National Aeronautics and Space Administration (NASA) as playing a key role in the disaster.[3]

Another issue that is particularly relevant for the transition of technology to the defense sector is the problem of introducing new technology into existing systems. It is well known that once technologies become entrenched, change is very difficult to effect. The technologies themselves become locked in through the coevolution of various technological systems. In the defense arena, the problem is exacerbated by practices that govern requirement setting, specification, and acquisition. This situation leads to historical path dependencies that constrain choices. For example, if there is a long history of using steel, the existence of detailed documents that govern use (standards and testing procedures) makes it more difficult to introduce new materials.

Social Dynamics and Decision Making

Addressing nontechnical issues that affect technology transition requires an understanding of social dynamics, including knowledge of who makes relevant decisions and who is accountable for what. In an establishment as complex as the military, not every person is responding to the same requirements and drivers. For example, reducing costs is likely to be at odds with other goals such as improving survivability and mobility. The evaluation and prioritization of competing objectives, and, ultimately, how decisions are made, are increasingly complex. In general, the chain of command and the decision-making process are much more hierarchical in the military than in private companies. This is especially true for innovative companies that are models for accomplishing successful technology transition.

One result of a hierarchical structure is that a materials specialist in the military is likely to be several steps removed from decisions that govern the adoption of new technologies, whereas the expert

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[3] B. Berger and L. Rains. 2004. Aldridge Says NASA HQ Overhaul, Approval of Agency Budget Top Priorities. SPACE.com, July 16. Available at *http://www.space.com/news/aldridge_report_040616.html*. Accessed July 2004.

on a Formula 1 race car team or in a small start-up company will likely have sole responsibility for materials choices. A group's size and social dynamics are key variables in this regard. A sports team is a relatively small group focused on a single, well-defined goal: winning the race. In contrast, the military is a huge, complex organization, with a wide range of short- and long-term goals. It is far easier to identify technological strategies that will win a race than to identify those that will win a war.

A challenge for the military in trying to accelerate the use of new materials is that of understanding how to extrapolate success stories from industry and sports venues to the defense sector. For example, for the aerospace industry, weight and strength requirements in materials are paramount, and they make material choices critical. It is unclear whether material properties have the same importance at the highest levels of the military. While the value of a new material may be evident to the technical team or end user, the material's adoption will likely depend on the real or perceived impact of the material or technology on high-level military goals.

The Culture of Innovation

In his presentation at the workshop, Joseph Tippens, executive vice president for business development, Universal Chemical Technologies, stated that technology and culture drive technology acceleration. He quoted William Souder, author of *Managing New Product Innovations,*[4] in presenting a list of traits with a strong negative correlation to technology acceleration:

- Degree to which jobs are narrowly defined;
- Degree to which authorities are perceived to be narrowly defined;
- Degree to which information flows are perceived to be top down in a hierarchy;
- Degree to which loyalty and obedience are perceived to be required;
- Degree to which rules, policies, and hierarchical organizational levels are perceived to be the character of the organization.

In contrast, Tippens also presented the following list of traits that create a culture for technology acceleration:

- Constant adjustment of tasks through "viral" cross-functional interaction;
- A sense of responsibility that replaces unquestioned authority and a shared commitment to success that exceeds defined functional roles;
- Communication that flows in all directions without regard to hierarchy;
- Emotional commitment to milestone achievement that overrides complex rules and policies; and
- Originality and creativity that are valued over short-term economic efficiency.

General Alfred M. Gray, U.S. Marine Corps (retired), also addressed institutional culture, saying that organizational characteristics can impede or enhance transition. He commended the Defense Advanced Research Projects Agency (DARPA) for an impressive number of transitioned products, citing the agency's operational characteristics and policies as contributors to this success. Consistent with the model described above for accelerated technology transition, he described DARPA's operation as small, flat, and flexible, with industry and academia as the principal performers. He also listed flexibility as a

[4] Wm.E. Souder and J.D. Sherman. 1994. Managing New Product Development. New York, N.Y.: McGraw Hill, p. 164.

TABLE 1.1 Typical Behaviors That Result in Cultural Differences

Ideation People	Execution People
Are prototype driven.	Are requirements driven.
Learn by doing.	Want to do it right the first time.
Say: what if?	Say: prove it.
Nurture infant technology.	Want to: kill the weak and move on.
Figure out: can it be done?	Decide: should we do it?
Fill the funnel: create new options.	Narrow the funnel: increase focus.
Objective: understanding.	Objective: delivery.

positive characteristic, as well as that of having many nongovernmental managers.

The Role of Individuals

Every major institution relevant to the discussion has subcultures that play a critical role in the development and transition of new technologies. As exemplified in the following sections, the interactions between subcultures within an organization play a vital role in determining the success or failure of technology transition. Successfully managing this interaction requires individuals who understand the values, working styles, and goals of different groups, and who appreciate the contributions that each group makes. These individuals are critical in fostering the communication that is the essence of successful technology transition.

Several workshop participants described some typical behaviors of people in discussing cultural differences that complicate deal making (see Table 1.1). Such differences in mission and approach can create culture clashes within institutions as well as between developers and outside customers. Both kinds of approaches are clearly necessary for innovation and effective technology transition, pointing to the importance of leaders and champions who can effectively manage people from both cultures throughout development and implementation. The engineers and scientists who are critical for innovation and development must be allowed to experiment, think freely, and fail on occasion. Ultimately, however, the successful transition of new technology will depend on the ability of managers to narrow the focus to technologies for which there is a compelling need and adequate business case, and on champions who will remove barriers, garner support, and ensure successful implementation and acceptance.

The importance of leadership was a recurring workshop theme. Tippens emphasized the importance of upper management in fostering cross-functional cooperation, communicating a sense of urgency, empowering people with authority to take risks, and rewarding performance. Several case studies presented at the workshop emphasized the importance of a champion to pave the way for a new technology or material. Perhaps the role of champions was most succinctly articulated by General Gray, whose advice was to "reduce the number of people whose job it is to say no, get rid of the risk-averse individuals, and figure out how to get around the people paid to be in your way." Accomplishing such objectives clearly requires champions with sufficient authority to remove barriers and manage what can be significant opposition to change.

General Gray also pointed out that there is a difference between education and training, emphasizing a need for improved education. In a hierarchical structure, people are highly trained in very specific aspects of their jobs, and generally have relatively narrow job descriptions with a strict chain of command. They are not educated on the overall goals of the program or on alternate strategies to accomplish these goals. Strictly defined procedures, processes, and manuals can conflict with the flexibility required in an innovative organization. An organization with a flexible culture would expect constant change, encourage risk taking, and call upon managers to make immediate decisions.

BRIDGING THE VALLEY OF DEATH

Volumes have been written about failures in technology transition and the disastrous consequences that befall companies that fail to recognize and adopt pivotal new technologies. For the military, the danger of not implementing new technologies is not that the DoD will go out of business, but that defense systems will be obsolete, expensive, and ineffectual. In Mastering the Dynamics of Innovation, James Utterback writes:

> A critical pattern in the dynamics of technological innovation—and one that should give every business strategist a great deal of discomfort—is the disturbing regularity with which industrial leaders follow their core technologies into obsolescence and obscurity. Firms that ride an innovation to the heights of industrial leadership more often than not fail to shift to newer technologies. Few attempt the leap from the fading technology to the rising challenger; even fewer do it successfully.[5]

At the workshop, Tippens contrasted what he terms "high-velocity" technology firms to industrial giants that cling to core competencies. He outlined the characteristics of these technology firms, as having—

- Shorter, more iterative processes than those of conventional firms;
- Simultaneous collaborative development;
- A passionate focus on end users' needs;
- A willingness to take risk, with risk anticipated and alternatives planned for; and
- Rapid prototypes, and early alpha and beta releases for immediate feedback.

These attributes are consistent with those identified by other workshop speakers as being essential for rapid technology transition. Iterative processes and collaboration are consistent with fostering communication and involving end users in the development process. Michael F. McGrath, Deputy Assistant Secretary of the Navy (Research, Development, Test and Evaluation), talked about the importance of involving stakeholders in the decision-making process, and gave several examples of successful transition that involved joint Navy-industry teams working together to research and select the best path for technology insertion. Focusing on end users' needs leads to the development of a business case for product implementation.

In the commercial sector, marketing plays a key role. If a technology concept is marketed to the customer as being ready for production when it is not, the corporation takes on a significant amount of risk in bringing the concept to production. If the new technology is marketed to the customer as a concept that is not mature but that can be available in, for example, 2 to 5 years, the customer might see that the company is thinking in terms of advanced concepts and positioning itself as well as the customer for the future.

Marketing plays a significant role in the success or failure of a technology. Marketing can be viewed as the rope bridge that spans the valley of death. Strain on the rope is created if the marketing department releases a concept to customers as being currently available. Customers then will not purchase the existing product but will wait for the company to implement the new technology. Such a delay in orders would cause current production to suffer. This pressure then forces the new technology into production before it is mature enough. The bridge could then break, and the champions and the technology they developed are left in the valley of death with a technology they cannot transition to production. Marketing strategies must therefore be controlled by the corporation. Strategically, the marketing department must be savvy enough to understand the technology and when it is reasonable to

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[5] J. Utterback. 1994. Mastering the Dynamics of Innovation. Boston, Mass.: Harvard Business School Press, p. 162.

make it available to customers.

Acceptable risk and the consequences of failure were recurring themes at the workshop because of their influence on technology decisions. For example, because new technology is a target for litigation in the auto industry, risk aversion has hampered the use of materials other than steel. There was agreement among all workshop participants that creating an innovative environment means anticipating and accepting risk.

Rapid prototypes and the importance of early feedback were also recurring themes at the workshop. McGrath reported that it is important to get the technology to the fleet early on so that the forces learn about and experience the capabilities of the technology. General Gray called on workshop participants to bet on the future, saying, "If it works, put it in the field." Flexibility was also identified as critical for effective technology transition, so that change can be accommodated throughout the development process.

Many of the essential ingredients identified during the workshop as being necessary to create a culture for innovation and technology transition are illustrated in the story of the early history of Xerox Palo Alto Research Center (PARC), a research and development group founded by the Xerox Corporation in 1970 on the campus of Stanford University. The failure of the Xerox Corporation to commercialize most of the exceptionally innovative computer technology created by the group is one of the most famous examples of failed technology transition.[6] The Xerox PARC group was charged with creating the office of the future. In *Diffusion of Innovation,* Rogers writes that among the computer technologies developed were the world's first personal computer, the mouse, laser printing, and local-area networks.[7] He attributes the incredible success of Xerox PARC to such company characteristics as outstanding personnel; a nonhierarchical management style that encouraged the free exchange of information and allowed an extraordinary degree of personal freedom; employees using the technology that they developed; and timing (judging that the time was ripe for innovations in personal computing). Resources were also abundant: Xerox invested $150 million in the research organization during Xerox PARC's first 14 years.

Of the computer technologies developed, only laser printing was commercialized by Xerox. Rogers attributes Xerox's failure to capitalize on other inventions to three major factors: (1) The company saw itself as being only in the business of office copiers, which is consistent with the characterization of many industry leaders as having a tendency to focus on what they see as their core competencies; (2) there were no effective mechanisms for transitioning the technology to the company's manufacturing and marketing divisions, which underscores the importance of communication and the active involvement of all stakeholders throughout the development cycle; and (3) there was a clash of cultures between the R&D group in California and Xerox headquarters on the East Coast. On this last point, Rogers writes:

> The button-down organizational culture at the Xerox Corporation headquarters clashed with PARC's freewheeling hippie culture. When East Coast corporate leaders traveled to PARC, they noted disapprovingly the beanbag chairs, the endless volleyball games, and the laidback management style of Bob Taylor. Unfortunately, Xerox executives rejected the promising personal computer technologies at PARC, as well as the work styles and lifestyles they observed there.[8]

Success stories in the literature and those presented at the workshop are similar in terms of the factors identified as essential to achieving rapid and successful technology transition. A particularly relevant study is a 2001 report by the Potomac Institute for Policy Studies entitled *Transitioning DARPA Technology*.[9] The report focuses on how well DARPA transitioned products into military systems over the

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6 D. Smith and R. Alexander. 1988. Fumbling the Future: How Xerox Invented, and Then Ignored, the First Personal Computer. New York, N.Y.: W. Morrow.

7 Rogers, 2003. See note 1 above, pp. 153-155.

8 Rogers, 2003. See note 1 above, pp. 155.

9 Potomac Institute for Policy Studies. 2001. Transitioning DARPA Technology. Arlington, Va.: Potomac Institute for Policy Studies. Available at *http://www.potomacinstitute.org/research/darpa.cfm*. Accessed July 2004.

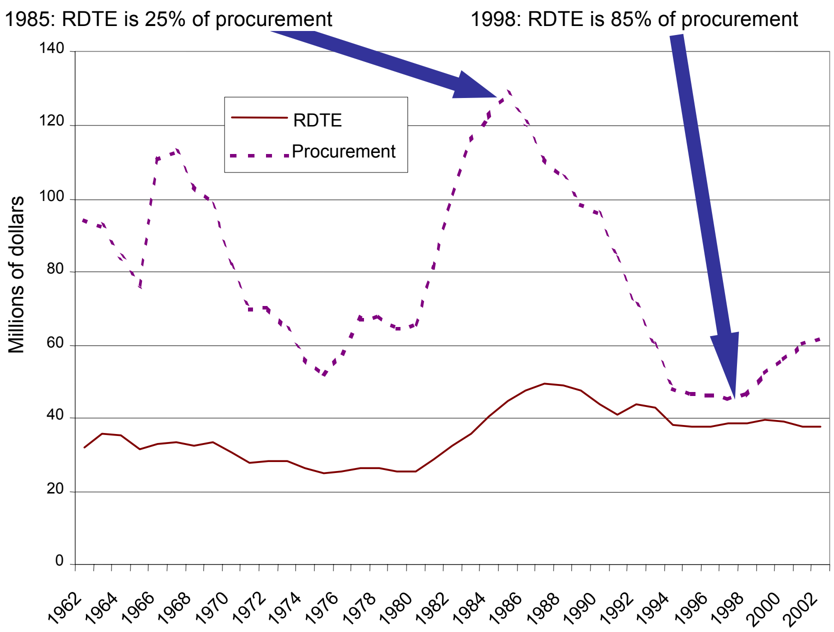

FIGURE 1.1 Department of Defense budgets for research, development, testing, and evaluation (RDTE) and procurement over time. SOURCE: General A. Gray, U.S. Marine Corps (retired), Military Needs for Technology Transition, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24, 2003.

past 40 years. One of the goals of the project was to identify factors that affect the agency's transition rate. Consistent with the message delivered by several speakers at the workshop, flexible management and contracting procedures were identified as being "a major benefit in dealing with industry and, ultimately, in transitioning to commercial and military markets."[10] An impediment to transition identified in the report is that DARPA has few effective mechanisms for continuing to market its products when programs end, particularly when a program manager leaves DARPA. In agreement with speakers at the workshop, the report acknowledged the importance of champions: "Transition success was highly dependent on the individual DARPA program managers, industry program managers, and Service contracting agents acting as a product champion team."[11] The report concludes: "It is likely that any structure or procedure that limits the program manager's sense of responsibility or options to transition his or her products will negatively affect the Agency's rate of transition."[12]

MAKING THE BUSINESS CASE

Joseph Tippens, Universal Chemical Technologies, argued that there is a strong and unique business case for materials science, which can help the DoD meet its goals in several areas, beginning with the weight reduction of systems and subsystems and leading to improved mobility, survivability, and lethality, while also offering significant capital and operating and maintenance cost savings. Michael McGrath, the Deputy Assistant Secretary of the Navy (Research, Development, Test, and Evaluation), emphasized that each successful technology transition is ultimately a deal that makes sense to all partners. For the commercial side, he listed three necessary conditions for a successful transition: a perceived need, a potentially effective and suitable solution, and a business case for investing. For the government side, he added two additional conditions: budgeted resources and an acquisition method.

Dramatic changes in recent years in both the private and government sectors have changed technology needs as well as budgets and funding priorities and the way that the military does business. This has created new challenges in technology transition to defense industries. General Alfred Gray, USMC (retired), told the committee that events in recent history that have influenced technology transition to the military include the end of the Cold War, the increased pace of technology development in the

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[10] Potomac Institute for Policy Studies, 2001. See note 9 above, p. ix.
[11] Potomac Institute for Policy Studies, 2001. See note 9 above, p. xi.
[12] Potomac Institute for Policy Studies, 2001. See note 9 above, p. x.

FIGURE 1.2 Competing pressures that drive the development process for new materials. SOURCE: R. Schafrik, GE Aircraft Engines, Technology Transition in Aerospace Industry, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24, 2003.

commercial sector, globalization, lower DoD budgets, and a more diffuse threat spectrum. He presented data (Figure 1.1) showing that in the past 10 years, the budget for procurement has been reduced substantially compared with the budget for research, development, testing and evaluation. A result of the sharp reductions in the procurement budget is that an increasing number of technologies are chasing fewer systems. He reported that the decreasing number of major developmental systems has reduced the opportunities for transitions to the military.

As illustrated in Figure 1.2, the development process is subject to competing pressures. Business needs, driven by customer needs and competitive market forces, in turn drive materials development. Improving performance and lowering cost are key factors in satisfying business and customer needs. Robert Schafrik of GE Aircraft Engines emphasized that the high introductory cost of new materials and processes must be offset by compelling customer benefit. It is also important to understand that the business process is iterative, making it imperative to be able to adapt to changing conditions and requirements.

At the workshop, Tippens outlined the business case for accelerated development. As indicated

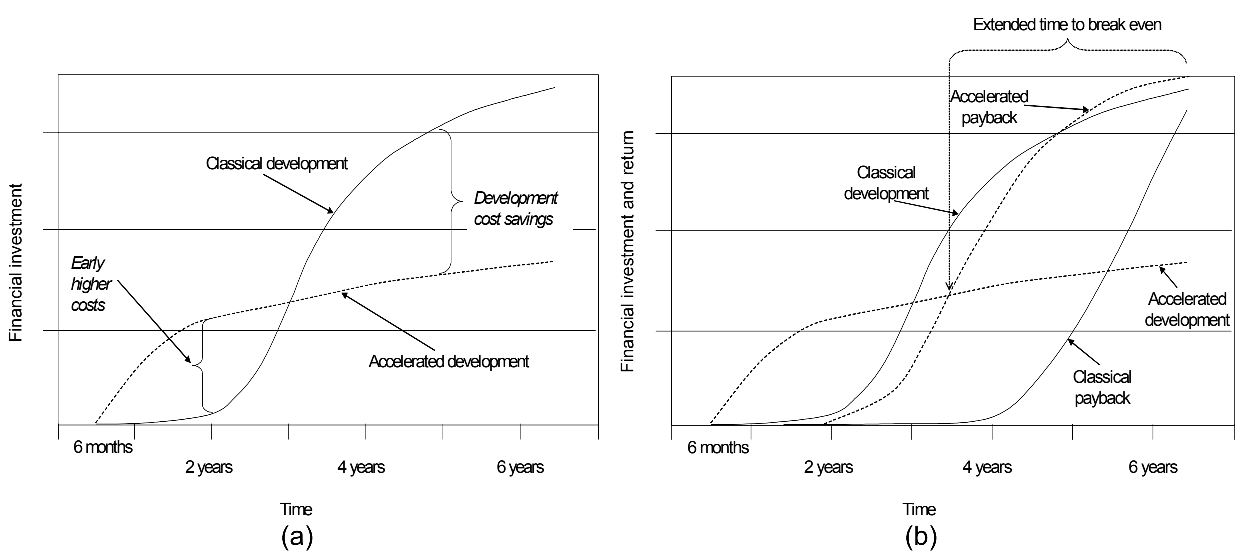


FIGURE 1.3 (a) Development cost and (b) return on investment for accelerated and classical development paths. SOURCE: J. Tippens, Universal Chemical Technologies, Inc., Technology Transition from Small Business Industry, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24, 2003.

TABLE 1.2 Typical Development Times for New Materials

Development Phase	Development Time
Modification of an existing material for a noncritical component	2 to 3 years
Modification of an existing material for a critical structural component	Up to 4 years
New material within a system for which there is experience	Up to 10 years—includes time to define the material's composition and processing parameters
New material class	Up to 20 years and more—includes time required to develop design practices that fully exploit the performance of the material and establish a viable industrial base

SOURCE: R. Schafrik, GE Aircraft Engines, Technology Transition in Aerospace Industry, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24, 2003.

by the graphs in Figure 1.3, initial costs are higher for an accelerated development path than for classical development. However, there is an overall cost savings and a faster return on investment.

Accelerating Materials Development

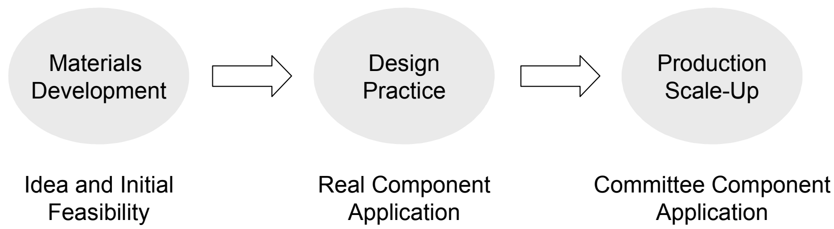
In his presentation at the workshop, Robert Schafrik emphasized the need to drastically reduce development times for new materials, saying that a decade is too long to mature new materials technology. As summarized in Table 1.2, he reported that typical development times range between 2 and 20 years. He called for rapid assessment of the value of new materials technology.

Schafrik contrasted the current approach to materials transition with that of the past and with what he expects it to be in the future. He described the past development approach as an empirical and heuristic-based "shotgun" approach by which, for example, an application would commit to an alloy before the alloy had been fully developed. There was an emphasis on characterization of the microstructure and limited properties, leading to many trials over many years. The issue, of course, is that it is impossible to test everything. As illustrated in Figure 1.4a, the past approach to the development process was sequential: a material was first developed, then improved, then modified to reduce costs and prepare for production, with testing cycles at each step. This process included feasibility studies, subscale demonstration, full-scale trials, and qualification. Schafrik described the situation for "technology push," in which materials were marketed to systems engineers and designers, typically in materials and processes organizations, with the goal of lining up funding commitments. A problem in this regard is the tendency to oversell.

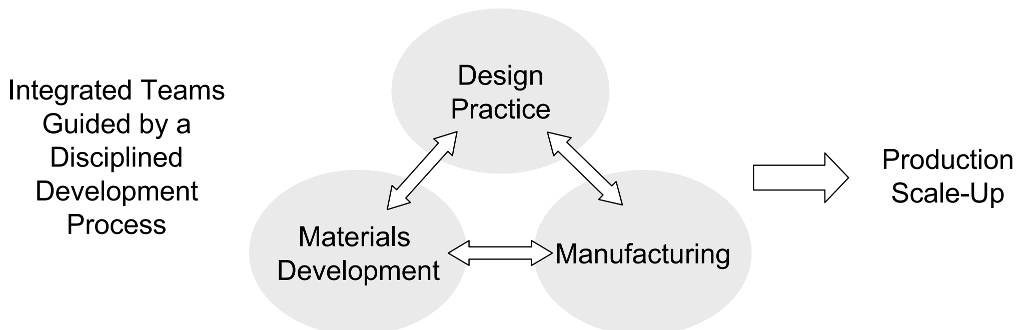
In contrast, the current development approach can be described as having begun to exploit material and process modeling and simulation. Schafrik credits DARPA's Accelerated Insertion of Materials (AIM) program for having revolutionized the thinking on and approach to materials development. He reports that fundamental knowledge is being used to develop models that allow behavior to be predicted, resulting in fewer and more focused iterations, and that statistical methods are being used for disciplined experimental design and analysis of results. As illustrated in Figure 1.4b, the current development process is integrated, with design practice, materials development, and manufacturing being guided by a disciplined development process leading to production scale-up.

Regarding customer needs, Schafrik describes systems engineers and designers as setting top-level requirements that are based on customer needs, with material and processing operations determining specific material requirements. He estimates the time frame for the introduction of a new commercial product to be between 18 and 24 months from the time the product concept is frozen to the point of product validation. Commercialization of such a product requires having suppliers onboard or establishing a manufacturing capability.

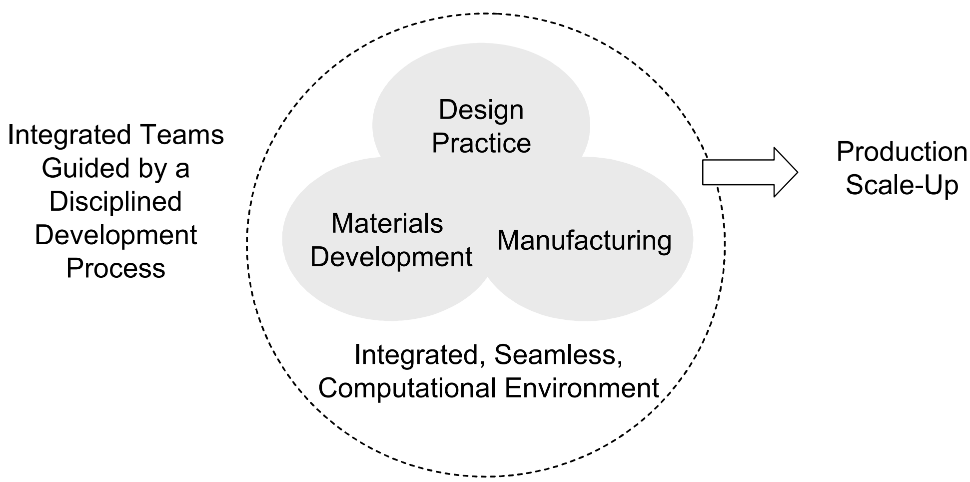
Schafrik's vision of the development approach of the future entails the full exploitation of materials modeling and simulation. He envisions modeling being used in conjunction with focused testing in order



(a) Past approach to materials transition.



(b) Current approach to materials transition.



(c) A model for materials transition in the future to accelerate development.

FIGURE 1.4 Models of materials transition. SOURCE: R. Schafrik, GE Aircraft Engines, Technology Transition in Aerospace Industry, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24, 2003.

to obtain accurate estimates of material properties and an understanding of microstructure evolution, as well as realistic estimates of the behavior of realistic samples, with typical defects and long-term behavior in harsh environments. Figure 1.4c characterizes the future development process as being fully integrated, with design practice, materials development, and manufacturing all integrated in a seamless computational environment, leading to production scale-up.

Modeling and simulation were highlighted by several workshop participants as making a positive contribution to accelerating materials development. Schafrik pointed to successes in superalloy disk

BOX 1.1
Methodology Adopted by the
Accelerated Insertion of Materials–Composites (AIM-C) Program
to Accelerate Materials Insertion

The partners in the Accelerated Insertion of Materials-Composites (AIM-C) program sponsored by the Defense Advanced Research Projects Agency wrestled first with the question: At what point is a material "transitioned" or "inserted"? Candidate endpoints included (1) the adoption of the materials technology by a design team, (2) certification of the structural component by the military, or (3) the successful use of the structural component in the field. AIM-C adopted the definition that a material would be considered as being transitioned when the structure was certified for use by the military. With this definition, AIM-C was then tasked with providing the foundation for the decision to certify. Thus, the AIM-C team had to include not only material developers and design personnel, but also the military officials who would need to recommend the component for certification. The composition of the team reflects a major issue raised by participants at the Workshop on Accelerating Technology Transition regarding partnership between creators and end users of new technology.

Once the definition of the endpoint was agreed, AIM-C partners tackled the concept of a window of opportunity. During the design process, the design team evaluates and selects materials at a given period, which may be only a few weeks or months long. During this window, the technical and business cases for new technology insertion must be made, and the relevant material parameters must be characterized with sufficient certainty that the program could go forward with the material at an acceptable level of risk. This limitation adds an element of urgency to the insertion process. If the window is missed, the material must wait for another opportunity.

Next, the AIM-C team assembled people with considerable experience in materials development and insertion and put them through an exercise to identify and categorize many of the issues that can impede or prevent materials insertion. For each of the resultant categories, a scale was developed to assess their maturity. The scale was based on the DoD's Technology Readiness Levels (TRLs), and under each of the nine levels, a series of sublevels, termed xRLs, was developed. These sublevels were designed to extend the maturity assessment to individual disciplines. This exercise highlighted the limitations of individual tools and made it clear that a methodology was needed within which the tools were used. The TRL-xRL matrix thus became the foundation of the AIM-C methodology. (The AIM-C concept of using tools within a larger methodology is addressed in Chapters 1 through 3 in the present report.) The AIM-C team used the TRL-xRL framework to ensure interaction and communication among the relevant personnel. The depth and breadth of the TRL-xRL concept have significant potential to provide structure to future partnerships between technology creators and end users and would provide breadth to the concept of viral development.

Finally, the AIM-C program discovered that technology creators and technology users, using the same TRL criteria, will evaluate the maturity of each technology differently. Miscommunication between groups can result from these variations. The AIM-C team worked to develop a TRL scale that was interpreted in the same way by both developers and users.

SOURCE: C. Saff. 2004. A New Way to Design Composite Structures. Presentation to the Innovative Design Workshop, Hampton, Va., March 2004, available at *http://www.darpa.mil/dso/thrust/matdev/aim/AIM%20PDFs/presentation_2004/general1_a.pdf*; accessed July 2004; and Glenn Havskjold, The Boeing Company. Personal communication, March 2004.

materials and polymer-matrix composites (see Box 1.1). He also reported that process modeling for casting and forging are demonstrating significant benefits using commercially available software tools; data used to set boundary conditions are crucial.

As discussed in Chapter 3, fundamental information input to models and data to validate output are essential to increasing the use of modeling and simulation. Saying that no one agency or company alone can accomplish all that needs to be done in this area, Schafrik called for a partnership between government, industry, and universities to develop and implement materials modeling and simulation tools. More specifically, he recommended that the Office of Science and Technology Policy sponsor a National Initiative for Aerospace Materials Modeling and Simulation (see Chapter 3). He argued that such an initiative is necessary to promote national competitiveness and to develop pre-competitive models and representations, and for the performance of necessary experiments. He pointed out that such an initiative is in line with the recommendations of the President's Commission on the Future of the U.S. Aerospace Industry, and that it would assist in attracting and retaining top-notch talent for materials science and associated disciplines.

Leveraging the Commercial Sector

General Gray reported to the workshop that the most significant long-term change in technology transition in the military is the current effort to better leverage the commercial sector. Michael McGrath expanded on this by describing several ongoing programs at the Department of the Navy focused on technology transition. He also reported that the Navy is trying to increase the visibility of emerging commercial technologies by interfacing with venture capital investors.

A speaker from the private sector, Joseph Tippens, suggested that the DoD has the opportunity to leverage billions of dollars of private equity and venture capital. He encouraged dual-use commercial development rather than technology development for isolated military applications, pointing out that it is possible to leverage technology platforms on hundreds of systems across all service branches as well.

Several workshop speakers discussed the advantages of using commercial off-the-shelf (COTS) technology. McGrath recommended taking advantage of the rapid cycle time of COTS technology to upgrade equipment and reduce system costs, but he also cautioned that change is an inherent aspect of using COTS components and must be planned for—for example, by developing an equipment infrastructure to handle future upgrades. Another advantage of utilizing COTS technology is that it goes a long way toward simplifying the procurement process. In speaking as a strong proponent of leveraging dual-use commercial development and private equity capital as a means of accelerating technology transition to the military, Tippens put forth a model in which industry, venture capitalists, academic research institutions, and the DoD would work together to leverage not only capital, but also information and data (see Figure 1.5).

BARRIERS TO TECHNOLOGY TRANSITION

The previous sections in this chapter described strategies and cultural aspects that foster innovation and technology transition. This section addresses potential barriers for the specific case of materials transition to the defense sector. Robert Schafrik of GE Aircraft Engines credited Arden Bement[13] in pointing out two chicken-and-egg dilemmas that occur in trying to introduce new materials: (1) Designers are reluctant to select a new material until it is evaluated in service, but a new material cannot be evaluated in service until a designer selects it; and (2) new materials do not gain market acceptance until their costs decrease, but costs will not decrease until the material gains market acceptance.

These two dilemmas tell us that rapid technology transition will require moving ahead with imperfect information. They also tell us that failure in rapid technology transition is a very real possibility. Workshop speakers unanimously identified risk aversion as a fundamental barrier to innovation and rapid technology transition.

The speakers also agreed that new materials should be introduced in the field as early as possible. If all stakeholders are engaged and if the full development and implementation cycle is flexible, early introduction allows maximum interaction between developers and users. This interaction can foster the type of communication that has been identified as critical for successful technology transition.

[13] Arden Bement, director of the National Institute of Standards and Technology. Biographical information available at *http://www.nist.gov/director/bios/bement.htm*. Accessed July 2004.

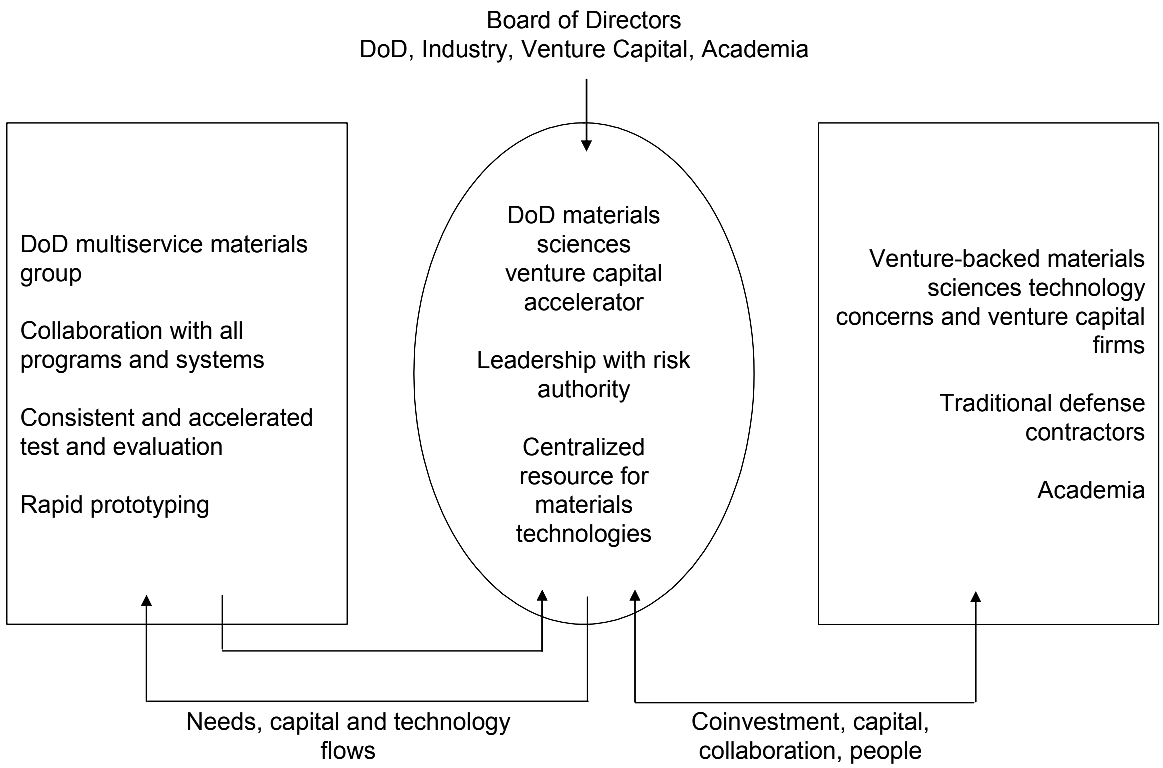


FIGURE 1.5 A model for accelerated technology transition to the military that utilizes traditional research institutions and leverages commercial development and venture capital. SOURCE: J. Tippens, Universal Chemical Technologies, Inc., Technology Transition from Small Business Industry, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24, 2003.

Another communication issue that arises when customers are not part of the development process is that developers have to market their technology to potential users. This can result in overselling a new material that has not been fully tested. In addressing the difficulty of evaluating new materials, Schafrik reiterated the conventional wisdom that the first information heard about a new material is usually the best thing ever heard about it. He attributes this occurrence primarily to initial claims based on data for a few properties and on test data generated from small lot sizes. He reports that little consideration is given to the effects of processing variations, and that there is a lack of understanding of the fact that defects ultimately determine properties and uses. Involving users in the development process can avoid such miscommunication because material characterization and testing can be tailored to specific applications.

Schafrik and other speakers emphasized the need for fundamental information on a variety of material properties, data from laboratory tests, and performance data in order to provide input to models and to validate modeling and simulation results. Collaborative efforts to create materials databases would benefit both the materials and the defense communities. These databases must include more than basic properties, and should extend to thermodynamic data and tribological data, including failure modes. Tippens recounted a recent experience of finding little consistency in materials and tribology testing protocols between cross-system groups, as well as within and across service branches. Such experience points to the need for communication and consistency in how data are reported. Improvement in the consistency and coherency of the data can be particularly important for better leveraging knowledge and capabilities in the commercial sector.

Other barriers to rapid technology transition are associated with bureaucratic issues inherent in huge organizations. At the workshop, McGrath called the military's requirements process a "confounding issue in government acquisition." In addition, the report of the Potomac Institute for Policy Studies concluded: "The Planning, Programming and Budgeting System and other manifestations of the Department of Defense's bureaucratic processes provide their share of pitfalls along the path [to transition] as well."[14] As discussed previously, it can be very difficult to introduce new technology into existing systems, in part because of the existence of detailed documents and standards that govern everything from materials specification and testing protocols to acquisition.

Another difficult challenge in technology transition to the military is that constancy of funding to full maturity is seldom available. Tippens addressed cultural differences between venture-capital industries and defense-technology companies that can hinder technology transition, pointing out that budgeting cycles in the defense industry favor established contractors at the expense of smaller companies and start-ups. General Gray reiterated the point, saying that budgetary considerations often discourage opportunity-driven strategies, and McGrath pointed to the 2-year budget lead time as an impediment to rapid technology transition.

Another cultural difference involves the development path. The venture-capital industry is based on rapid deployment and market entry, whereas the path in defense industries tends to be much slower. Tippens explained that the time value of money and the internal rate of return in the venture-capital industry, in which the expectation for return on investments is that a critical amount of revenue will be reached in 3 to 6 years, do not match the defense culture. These differences interfere with the ability of the defense sector to leverage private equity capital.

CONCLUSIONS AND RECOMMENDATIONS

Bridging the valley of death is a challenging, long-term process that begins at the conceptual stage of a new material or technology and continues through its implementation and acceptance. The essence of technology transition is communication. Workshop participants consistently described successful technology transition as a long-term dialogue and partnership between the creators and end users of new technologies. Because materials in and of themselves are rarely products that can be directly linked to defense needs, continuous communication between developers and users is particularly critical in order to ensure that new materials are considered for and ultimately used in components and systems. Prototypes should be put in the hands of potential customers as early as possible so as to foster communication. Management buy-in is essential, as are champions with sufficient authority to remove barriers, garner support, and ensure successful implementation and use. In this view, technology transition is a collaboration among all stakeholders that drives an iterative process of development, implementation, and acceptance.

A central theme of the workshop was the importance of creating a culture that fosters innovation, rapid development, and accelerated technology transition. Success stories from industry, sports, and the defense sector point to flexibility, a willingness to take risks, open communication without regard to hierarchy, a sense of responsibility that displaces the need for top-down authority, and a commitment to success that exceeds functional roles as being key elements of the desired culture. Creating such a culture has several fundamental implications: people must be empowered to take risks; failure must be anticipated and planned for; and teamwork and collaboration must be championed over individual accomplishments and success. In this model, the idea that "failure is not an option" is replaced by the understanding that "failure provides lessons learned in an innovative environment."

Every major institution relevant to this discussion has subcultures that play a critical role in the development of new technologies and in determining the success or failure of technology transition. The engineers and scientists who are critical for innovation and development must be allowed to experiment, think freely, and fail on occasion. The successful transition of new technology depends on the ability of managers to narrow the focus to technologies for which there is a compelling need and to work with

[14] Potomac Institute for Policy Studies, 2001. See note 9 above, p. x.

potential customers to develop an adequate business case. Successfully managing this type of interaction requires leaders who understand and respect the values, working styles, and goals of different groups, and who can also effectively initiate and sustain communication among the stakeholders across all organizational and institutional boundaries.

A challenge for the military in trying to accelerate the use of new materials is that of overcoming cultural traits associated with hierarchical and rule-bound organizations that impede technology transition and tend to favor traditional defense contractors over smaller companies and start-ups. Overcoming this challenge means decentralizing decision making, simplifying procurement and acquisition processes, shortening budget cycles, providing consistent funding through development and maturation, making greater use of off-the-shelf technology, and valuing innovation over short-term economic efficiency.

It is also necessary to update standards and testing procedures that are based on entrenched technologies in order to make it easier to introduce new materials. In general, the operations infrastructure must be flexible enough to meet the demands of highly collaborative, fast-paced, high-risk projects, and must be able to accommodate change during the development process. The technical team and end users must be part of the decision-making process. Although the value of a new material may be evident to developers and customers, in an establishment as large and complex as the military, the adoption and acceptance likely depend on the real or perceived impact of the material or technology on high-level military goals.

Although creating a culture for innovation and rapid technology transition requires significant changes and a concerted and sustained effort, the potential rewards are substantial. The case for making these changes to accelerate the transition of materials technologies is particularly compelling because of the unique ability of new materials to contribute to a wide range of technical objectives (e.g., increased mobility and survivability), while also offering significant capital and operating and maintenance cost savings. Although initial costs are higher for an accelerated development path, there is an overall cost savings and a faster return on investment than for classical development. Perhaps even more compelling is that by better matching the development and deployment time frames in the venture-capital industry, the military can leverage dual-use commercial development and billions of dollars in private equity capital.

Recommendation 1. The Department of Defense (DoD) should endeavor to create a culture that fosters innovation, rapid development, and the accelerated deployment of materials technologies.

Success stories from commercial, sports, and defense industries suggest that the characteristics of such a culture include the following:

- Acceptance of risk, anticipation of failure, and plans for alternatives;
- A flexible environment with the ability to accommodate change during the development process;
- Open communication in all directions without regard to hierarchy;
- A widespread sense of responsibility and commitment to success that exceed defined functional roles;
- Valuing of innovation over short-term economic efficiency; and
- A passionate focus on the end-user's needs.

Evaluating and implementing the following actions will enable the DoD to create a culture that fosters rapid development and breaks down barriers to rapid technology transition:

- Introduce flexibility that reduces budget lead times and provides consistent funding during the technology development stage through full maturity,

- Make better use of commercial off-the-shelf technology,
- Implement shorter and more iterative design and manufacturing processes,
- Simplify procurement and acquisition processes,
- Update standards and testing procedures to make it easier to introduce new materials and processes, and
- Decentralize decision making throughout the process.

Leveraging private equity capital and pursuing dual-use commercial development can also be effective. Investments in materials processes and technology will offer the DoD the opportunity to leverage materials technology for defense systems across all service branches.

2

Methodologies and Approaches

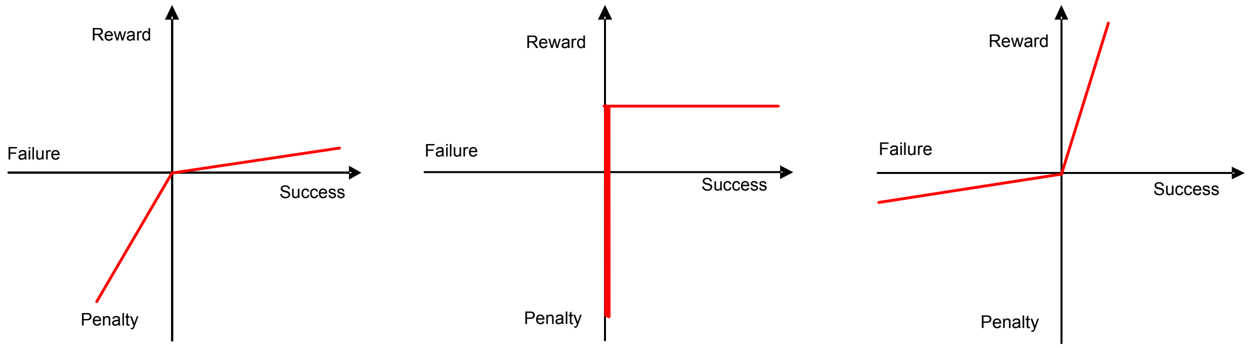
Many of the best practices discussed at the Workshop on Accelerating Technology Transition function by altering the risk–reward relationship of the military customer and the suppliers of high-technology materiel. This balance can be changed when both parties work to the desired technology function rather than to specification. This strategy results in the ability to both better quantify the rewards associated with success and the ability to mitigate the risk of failure.

LESSONS LEARNED FROM A COMPARISON OF RISK–REWARD MODELS

The risk–reward relationship for success or failure in military systems was noted by many speakers at the workshop as being a primary barrier to the insertion of new technologies into military systems. The risk–reward structures for military systems are shown schematically for noncritical and critical technologies[1] in Figures 2.1 (a) and (b), respectively. The reward for success in a noncritical technology in military systems is significantly less than it is in the commercial sector. Moreover, as the technology becomes more critical for system functionality, the penalty for any failure increases and can become very large compared to the reward for success. At the limit, the penalty for a single failure of a critical technology is infinite. In fact, the Department of Defense (DoD) practice of punishing those who cause failure was cited by speakers from military and industrial organizations alike. They described the severe penalties faced by DoD program managers who introduce a technology that fails, even in preliminary tests. This attitude within the DoD that so heavily penalizes failure and does not provide appropriate rewards for success breeds a culture that is, by nature, averse to transitioning new technology very rapidly, or at all.

According to workshop presenters, the contrast in risk–reward structures between military and industrial customers is most apparent in companies that have interacted both with the DoD and with commercial customers. Joseph Tippens, Universal Chemical Technologies, described one extreme when he spoke of the entrepreneurial efforts supported by venture capitalists. In the venture capital experience, 80 percent of high-risk investments are expected to fail. However, the 20 percent that succeed are predicted to have very large returns on investment. Figure 2.1(c) demonstrates the high value of success and the relatively low penalty for failure on a particular technology. As the success level increases, the reward increases rapidly. However, the penalty for failure, while present, is not as severe as the rewards for succeeding. This approach gives a very strong incentive to attempts to create successes, and it is accepting of failures as a part of the process. This pull is key to rapid technology

[1] For purposes of this discussion, a critical component is defined as one that can cause complete loss of system functionality if it should fail.



(a) Department of Defense view of the reward structure for noncritical technology.

(b) Department of Defense view of the reward structure for critical technology.

(c) Venture capitalist view of desired reward structure.

FIGURE 2.1 Different views of the reward structure for new technologies.

transition in the entrepreneurial commercial arena.

With fear of failure and its accompanying penalty as a key barrier to moving forward with new technologies in military systems, far less focus is placed on the potential gains to be realized should a technology be successful in the long run. For almost every new technology awaiting insertion, there is a conservative fallback solution that has lower performance, but a much lower risk of failure. Ned Allen of Lockheed Martin expressed the importance of the fallback technology in terms of the number of new technologies inserted per year. He postulated that the real rate of technology insertion is determined by the status of the fallback position. The insertion of new technologies into military systems is, therefore, most rapid and effective when existing technology fails: there is a crisis and there is no fallback position.

In contrast, Rich Bushman of 3M indicated that the technology advancement process at 3M is often driven by examining both the costs to be incurred and the potential for success or failure, and then comparing those with the entitlements to be accrued should the new technology be successful. Figure 2.2 indicates that, unlike the case with traditional goal setting, the focus becomes the maximum benefit to be accrued in the event of success, that is, the performance that the project is "entitled" to. Using this approach, one can set realistic goals in terms of achieving some large fraction of the "entitlement." For a greater acceleration of technology transition, several of the participants felt that acknowledging and appreciating the benefits as well having better estimates of the risks would aid in the transition.

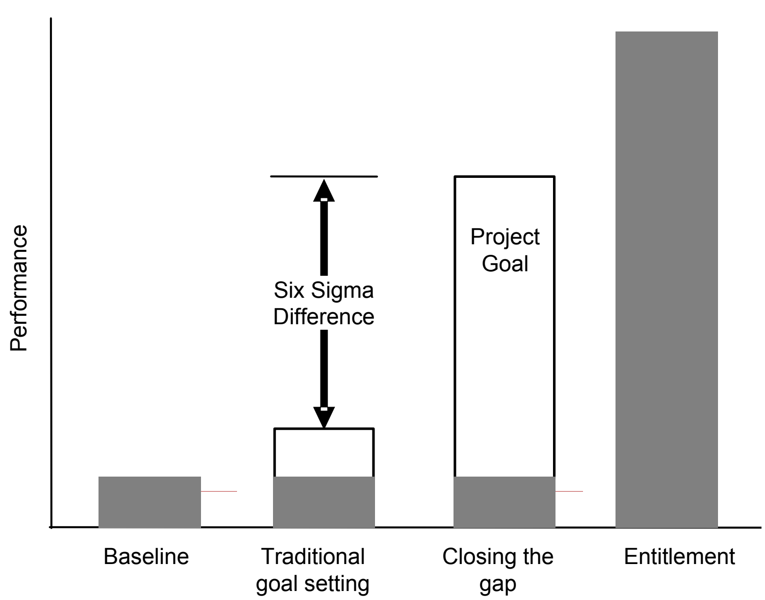


FIGURE 2.2 Six-sigma view of available benefits. SOURCE: Reprinted, by permission, from Sigma Breakthrough Technologies, Inc. Copyright 2003 by Sigma Breakthrough Technologies, Inc., San Marcos, Tex.

By placing appropriate metrics on rewards for success as well as on penalties for failure, workshop participants said, the DoD managers could select and advance technology programs based on an appropriate cost–benefit model. Those programs that had a high level of potential performance could then be moved forward rapidly even if there were known risks of failure. Moreover, this could be done in the absence of any crisis, as seems to be necessary in the current DoD environment for the rapid transition of technology.

Risk aversion is critical, according to workshop participants. In fact, much of the work in the Accelerated Insertion of Materials (AIM) program was directed at resolving issues of risk, uncertainty, and confidence. Technical uncertainty is a major reason for rework cycles in product development aimed at correcting problems in the design. In turn, rework is the primary cause of cost and schedule overruns. If a technology has progressed far enough that insertion pilot programs are feasible in parallel with ongoing product-development programs, this can provide the needed application experience. This is one strategy to overcome the risk aversion of future product development programs.

SUCCESSFUL BEST PRACTICES

Based on the workshop presentations, the committee identified three corporate best practices that are effective at accelerating technology development and product introduction into the public marketplace.

Best Practice 1: Developing a Viral Process for Technology Development

One successful best practice identified by the committee is that of developing a "viral"[2] process for technology development. This process involves quick, iterative development cycles and prototyping of materials and products; free, open communication with all stakeholders; agile manufacturing processes;[3] and realistic modeling of materials and processes, system performance, and cost.

Quick, Iterative Development Cycles and Prototyping

From the perspective of several industries, iterative processes for research, product development, marketing, manufacturing, and accounting are necessary, and they must be done in close consultation, if not actual collaboration, with potential customers. Two examples were provided at the workshop of quick development cycles and prototyping in order to accelerate the insertion of new materials and technologies within the DoD. At the workshop, General Alfred M. Gray, U.S. Marine Corps (retired), described the rapid development of a shoulder-mounted weapon. The design was improved and its deployment was accelerated using feedback on prototypes provided for use to soldiers in field conditions. Anthony Mulligan, president of Advanced Ceramics Research, presented to the workshop attendees an example of that company's recent successful viral development of small, surveillance uninhabited aerial vehicles. This was accomplished by putting several generations of prototypes into the hands of U.S. troops stationed in Iraq. By having the end user involved in such a way, the development process is constantly focused on making the new technology meet the end users' needs.

Prototyping is not a new concept for the Defense Advanced Research Projects Agency (DARPA). In 1986, the President's Blue Ribbon Commission on Defense Management (the "Packard Commission")

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[2] "Viral" in this context means infectious, such that the process provides 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.

[3] "Agile" in this context means well-regulated manufacturing processes that are able to react to perturbations and continue to produce quality products. Process control strategies that meet this goal include 6-sigma, and disciplined design of experiments concepts.

recommended that DARPA take the lead in demonstrating the value of prototypes for reducing cost and technical uncertainties before formally committing to acquisition.[4] DARPA experimented with various forms of prototyping, and the agency developed a successful model in forming partnerships between the warfighter and the supplier. A 1997 DARPA report on technology transitions[5] describes DARPA's approaches to transitioning basic technologies, ranging from fostering new methods for making high-performance materials to creating major transitions such as the F-117.

Rapid development can be hindered if the development team focuses on improving a material, process, or system far beyond what is needed. At the workshop, Dave Tilles from Northrup Grumman described the company's success in creating a production-ready, biodetection system for the U.S. Postal Service; the system was fielded, tested, and certified within 18 months. One of the primary reasons for this success was the multidisciplinary team that kept the development going without getting bogged down in any one aspect of the process.

All workshop participants experienced in rapid technology development using the iterative development cycle acknowledged that challenges or opportunities arise throughout the process. For example, a material that works well in the laboratory may prove difficult to work with in manufacturing. In such cases, it is important to acknowledge the shortcomings and rapidly move toward addressing them. What might be perceived as failure by some may be viewed by others as new information about a potential bottleneck to development. The key to rapid technology development is to virally incorporate the knowledge into the development process and to modify the materials, fabrication processes, and systems as needed.

Agile Manufacturing Processes

For new technologies that require the development of new materials, there can be significant technical challenges and long time delays in transitioning from laboratory-scale materials, to generic, larger-scale prototyping, to full-scale, complex parts. If different processes must be designed in order to create these materials at different stages, new sets of increasingly difficult problems may have to be solved at each stage. These problems may include, for example, increased variability in materials properties and performance, below the tolerance limits. Agile manufacturing processes are needed for use at all stages in materials development, from materials development, to prototyping and pilot production, to full-scale production.

An example of an agile manufacturing process is that of Laser Additive Manufacturing (LAM), recently implemented under the DoD Manufacturing Technology Program. It was one of two technologies to receive the 2003 Defense Manufacturing Technology Achievement Award.[6] The LAM process produces parts built one layer at a time using stereolithography and is controlled by software that converts a computer-assisted data file to a sliced format corresponding to each processing step. Aluminum pylon ribs for the F-15 Strike Eagle were failing prematurely and were in low supply owing to use of the fighters in Iraq. The LAM process was used to manufacture ship sets made from titanium in only 2 months, meeting the increased demand for aircraft mission availability, improving aircraft safety, and extending the pylon part life by a factor of five.

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[4] National Defense University. 1986. Report of the President's Blue Ribbon Commission on Defense Management. Available at *http://www.ndu.edu/library/pbrc/pbrc.html*. Accessed July 2004.

[5] Defense Advanced Research Projects Agency. 1997. Technology Transition. Available at *http://www.darpa.mil/body/pdf/transition.pdf*. Accessed July 2004.

[6] DoD ManTech Awards. 2003. Available at *http://www.dodmantech.com/Award/CY03/2003.html*. Accessed July 2004.

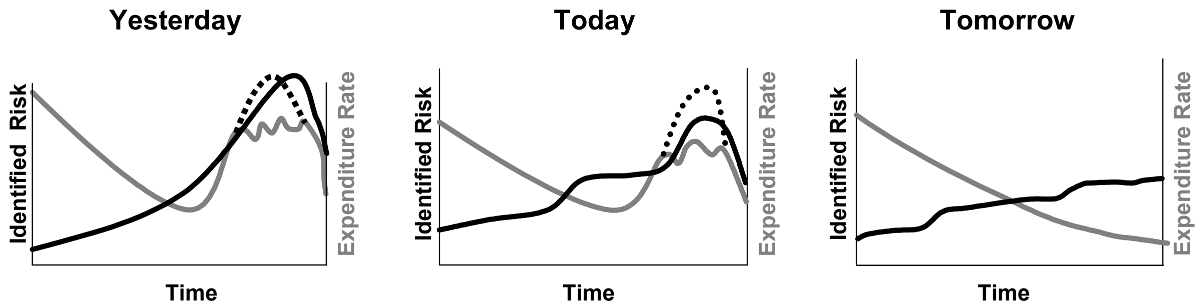

FIGURE 2.3 The change in perceived risk and expenditures with time that the Accelerated Insertion of Materials program achieved. SOURCE: R. Schafrik, GE Aircraft Engines, Technology Transition in Aerospace Industry, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24, 2003.

Modeling of Materials and Processes, System Performance, and Cost

Agile manufacturing processes are not possible for many materials and applications. Robert Schafrik, of GE Aircraft Engines, described the ramifications of having to scale up processes from initial feasibility studies through manufacturing. Schafrik made the key point that in many systems, particularly for critical components, the perceived risk of failure actually increases with time as the materials become more complex to manufacture and the demands on the technology become greater. The perceived risk of failure increases because of the challenge of scaling up structures from laboratory-size samples to full-scale parts, while keeping the complex materials, their microstructures, and their resulting properties constant. A discovery of new materials with specific combinations of properties is usually based on measurements of small, uniform samples. When the materials are fabricated in larger parts with more complex geometries, the fabrication processes lead to material inhomogeneities that result in inhomogeneous properties. Significant research and development is required to modify the fabrication processes to produce the designed spatial distribution of materials properties needed for the application.

As the parts become larger and more complex, two or more such scale-ups are sometimes required before making the final part. (Appendix C contains a more detailed description of the complexity of the development of critical components and the problems and risks that emerge in moving from the laboratory version to final part in development process.) The only way to accelerate this process is to use modeling of materials processing and properties to design fabrication processes that circumvent one or more scale-up cycles. Many modeling tools already exist, but more are needed. The DARPA AIM program has recently demonstrated the ability of modeling tools for materials and processes to effectively reduce the risk over time in complex new materials insertion projects; the two demonstration projects were for polymer composites and superalloys for aerospace applications. A comprehensive suite of materials modeling software and data is needed to accelerate the development and insertion of a wider range of material systems.

The change in perceived risk and expenditures with time that the AIM program achieved is represented in Figure 2.3. A vision for the ability of modeling tools to dramatically lower risk in technology development and insertion is embodied in the schematic entitled "tomorrow."

Detailed, physically realistic models of materials and materials processing could be used to design new materials and processes for specific high-performance applications. Materials modeling could not only be used to establish the average performance of new materials, but it could also be used to establish the range of materials performance likely as a result of processing variability and of the application environment. Average materials property behavior is not enough; three sigma properties are also needed.[7] Some materials cannot be formed by agile manufacturing processes; here, modeling materials and processes can provide the alternative means of agility.

In terms of accelerating the initial selection of materials, combinatorial and high-throughput materials research methods show great promise in developing needed materials property data as inputs to modeling and for differentiating competing materials and processes. In the areas of polymer science and catalysis, combinatorial research methods have dramatically reduced the time and cost necessary to identify and optimize new materials for applications as diverse as polymer coatings for marine structures and organic scaffolds for tissue engineering. New, high-throughput measurement methods are being developed for a wide range of organic and inorganic systems that could accelerate the selection of the best materials for a specific application, as well as stimulate the development of a deeper fundamental understanding of new materials and their properties.[8]

There is a strikingly effective tool for aiding the insertion of high-performance, multifunctional materials in America's Cup sailboats and Formula 1 racing cars—it is system-level software that quantifies how system performance changes with the insertion of new materials in new designs. In the case of America's Cup yacht,[9] new mast materials and designs were incorporated into ship handling and meteorology models in order to predict boat performance relative to that of competing boats. The accurate modeling of system performance, combined with measured behavior of prototypes, identified certain new materials and designs as being critical to ultimate system performance. Such modeling in DoD systems will aid in setting priorities for the wide range of new materials that could be inserted, and will increase the awareness of the capabilities of materials available for future exploitation.

Before advanced materials or new technology can be successfully brought to market, the economics of manufacturing processes must indicate some level of profitability. In areas of technological change, decision makers cannot afford to rely on cost-estimation techniques that are set up for traditional accounting purposes. These techniques cannot be used effectively to assess the cost implications of environmental aspects of process development. Knowledge of cost and environmental issues at the design stage is invaluable, since 70 to 90 percent of cost and emissions are determined by the product design; the remainder is due to control of the manufacturing process.

The construction and use of process-based technical cost models, described by Joel Clark of the International Motor Vehicles Program at the Massachusetts Institute of Technology (MIT), allows the estimation of manufacturing costs. Such models are especially important for defense systems, since the cost of the testing and evaluation of components made with new materials can equal one-third of the cost of manufacturing. Models are developed through collaboration with technology developers. By varying input parameters, sensitivity analyses aid in understanding the prime contributors to processing costs and may suggest nonobvious approaches to cost reduction. Further, current competitive processes can be assessed in comparison with the new technologies. This technique, developed by the Materials Systems Laboratory at MIT, has been used to successfully predict manufacturing costs for numerous processes in various industries.[10] This modeling methodology has been used extensively to assess process economics in various developmental industrial processes. An understanding of the economic factors can help researchers and system developers optimize manufacturing conditions and work toward testing the performance of materials and fabrication systems that seem to be the most economically viable.

This intersection of technical performance and economic performance is vital for the successful

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7 The Greek letter s (sigma) refers to the standard deviation of a population. Sigma, or standard deviation, is used as a scaling factor to convert upper and lower specification limits to Z. Therefore, a process with three standard deviations between its mean and a specified limit would have a Z value of 3 and commonly would be referred to as a three sigma process.

8 E. Amis. 2004. News and Views: Combinatorial Materials Science, Reaching Beyond Discovery. Nature Materials 3:83-85.

9 R. Kramers, Team Alinghi SA. 2003. America's Cup Technologies. Presented to the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24.

10 J.P. Clark, F.R. Field III, and R. Roth. 1997. Techno-Economic Issues in Materials Selection. ASM Handbook, Vol. 20, Materials Selection and Design. Metals Park, Ohio: American Society for Materials, pp. 225-265.

TABLE 2.1 Comparison of Formula 1 Race Car Technology Insertion Teams and Military Aerospace Market

Formula 1	Military Aerospace
Open specifications	Ultimate in detail specifications
Open processes	Use only our qualified processes
Constant improvement	Prove it will work
Rapid design cycles	New vehicle every 10 years

SOURCE: R. Aubrecht, Moog, Inc., Technology Transition Approaches at Moog, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 25, 2003.

commercialization of new materials, as Joel Clark and also Charles Wu of the Ford Motor Company indicated at the workshop. Wu described the process for the implementation of new materials and processing technologies in automotive applications. He suggested that the development of a business case and an understanding of cost are critical for technology transition in the commercial sector. The establishment of cost (i.e., functional) requirements and the business case early in the process can provide a means for terminating a project early, if warranted, and for allocating funds to technologies that have a higher probability of meeting all of the functional requirements—thus accelerating the transition of a "more deserving" technology. Moreover, by conducting this analysis early in the process, critical cost and business case issues can be addressed earlier in the development process—again accelerating transition of technology. Tools that can be used for cost estimates at an early stage in the design process are described in a recent report of the National Research Council.[11]

Best Practice 2: Increasing Reliance on Functional Requirements Rather Than on Specifications

A second successful best practice identified by the committee is that of increasing reliance on functional requirements rather than on specifications. One of the key limitations to the rapid insertion or development of new technology, particularly for the DoD, is the lack of information given to vendors about the relevant functional (includes cost) and technological needs. Instead, strict adherence to detailed but incomplete specifications is expected. The benefits of the successful functionality approach, known at Moog as concurrent engineering-plus, were described by Richard Aubrecht of Moog in his contrast of two separate business models for different markets served by Moog: Formula 1 race car teams and the military aerospace market (see Table 2.1).

Using the team-based approach with parallel development and constant iteration of design cycles, a new product for the Formula 1 market could be produced, tested, and certified for use in approximately 8 months between its initial development and volume production. This time frame is in stark contrast to the dramatically longer period for the military aerospace market, even though the particular systems and components are remarkably similar. The key difference is in the level of risk that the two customers are willing to take, which influences every aspect of the enterprise and, for military aerospace systems, eliminates the possibility of using the concurrent engineering-plus concept.

Military specifications have been essential for purposes of certifying that a particular material or system will have an extremely low probability of failure in use. However, for the development of new technologies, specifications reduce the ability to rapidly implement existing knowledge and technologies developed for nonmilitary systems by the different vendors who are also stakeholders in the overall development process. Most of the industry participants in the workshop stated that having an understanding of the desired functionality, including the use environment, would significantly accelerate finding the right material and the right technology solution, and therefore accelerate technology transition.

[11] National Research Council. 2004. Retooling Manufacturing: Bridging Design, Materials, and Production. Washington, D.C.: The National Academies Press.

This sentiment was echoed strongly by Northrup Grumman's biohazard detection team. This team, with the concurrence of the U.S. Postal Service, focused on operational success rather than on specification compliance.

At the workshop, Rich Bushman from 3M described how the selection of a proper abrasive material was hindered because the customer would not tell 3M how the material would be used. Based on incomplete specifications, an inefficient selection cycle ensued, and a candidate material was offered, evaluated, and rejected. The specifications were then refined to include new, albeit incomplete, information, and the cycle was repeated until a suitable material was identified. It needs to be noted that increased reliance on functional requirements rather than on specifications can only be implemented by having all stakeholders involved and by sharing information, as discussed in the subsection on Best Practice 1.

Best Practice 3: Developing a Mechanism for Creating Successful Teams

A third best practice identified by the committee is that of developing a mechanism for creating and recreating successful teams, independent of the industry and sector, as new products are envisioned.

The success of committed, multidisciplinary teams implementing iterative prototyping and working to functional requirements rather than to specification was brought up with respect to many different industries and in many different forms throughout the workshop. From Formula 1 race cars to America's Cup sailboats to aircraft, this approach needs to be based on parallel, iterative development processes, with rapid information dispersal that is described as the viral spread of information (whereby any new knowledge is infectious and is instantaneously dispersed throughout the team, and is self-propagating throughout the development process). Should an issue be discovered in the manufacturing processing of the material, this information would then rapidly be transferred to other materials development processes as well as to the testing and verification processes. Likewise, the solution to an issue that has arisen could emerge from this process. Joseph Tippens of Universal Chemical Technologies spoke of this as a constant adjustment of tasks through viral cross-functional interaction.

The concept of technology incubators formed by people having the right technologies, the right team skills, and the right financial support is not new. A recent report from the Institute for Defense Analyses concluded that incubators are needed to accelerate technology transition in the military.[12] Another recent report discusses recommendations for structures that could be created in the DoD to lead to greater technology transformation.[13]

The challenge in the case of accelerating technology transition in military systems is that the roles of the military and its suppliers in such an enterprise will be distinctly different from any of those that now exist in the venture-capital world. This is so because the military may be acting as the venture capitalist, technology developer, and the customer. According to the workshop presentations, all successful transitions to the military had the military customers as part of the team from the beginning, in order to ensure meeting the military's high performance requirements. There may be other goals, such as minimizing initial and life-cycle costs that must be fully disclosed by the military customer in order to maximize the chances of success. The highest levels of the DoD must support the creation of incubators and be committed to working with them effectively to implement new technologies. The creation, management, and interaction of multidisciplinary teams with the DoD cannot be ad hoc or the teams will

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[12] R.H. Van Atta and M.J. Lippitz, with J.C. Lupo, R. Mahoney, J.H. Nunn. 2003. Transformation and Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs. Vol. 1: Overall Assessment. IDA Paper P-3698, Log: H 03-000693, Alexandria, Va.: Institute for Defense Analyses, April. Available online at *http://www.darpa.mil/body/pdf/P-3698_Vol_1_final.pdf*. Accessed July 2004.

[13] U.S. Department of Defense. 2003. Transforming the Defense Industrial Base: A Roadmap. Washington, D.C.: U.S. Department of Defense, February. Available online at *http://www.acq.osd.mil/ip/ip_products.html*. Accessed July 2004.

likely be unsuccessful.

Methods for encouraging movement toward the best practices described above are not obvious, and it is not clear how to structure the technology incubators for success. It is likely that (1) there are a number of different successful structures, and (2) the organizational management of the incubator might be more or less successful, depending on the type of technology.

Along with the development of methods to promote successful technology incubators, a major hurdle to overcome in transitioning to such a structure will be the determination of methods for measuring the success of any given scheme. Methods to assess the performance of the technology transition scheme must be delineated so that investments in the more successful structures can be more frequently realized. Methods for assessment must also provide some measure of accountability within the organization that is funding the development. By developing technology incubators and finding performance indicators to assess their success, the time duration for technology transition from conception to implementation is likely to decrease.

It is not clear that technology incubators alone can overcome what is called the Valley of Death concept—that is, the gap between technological invention and acquisition; there is still a large disconnect between military acquisition and what the incubators can create. One possible model is the venture-capital firm, In-Q-Tel, sponsored by the Central Intelligence Agency. This firm's mission is to identify and invest in cutting-edge technology solutions that serve U.S. national security interests.[14] Through this paradigm, the intelligence community can procure technology without going through the standard procurement and acquisition processes. It is unclear, however, whether this model will work for large-scale activities. Perhaps a champion needs to be found at the level of the Secretary of Defense or the Joint Chiefs, and a small, venture-like Skunk Works be nucleated. The military mindset of small rewards and large punishments, respectively, for success and failure tend to defeat any motivation generated by individuals. If this approach were changed in a Skunk Works venture, it would be more consistent with the military's overarching goals to have the best equipment possible for the warfighter.

CONCLUSIONS AND RECOMMENDATIONS

The committee concludes that there is no single solution that will accelerate the insertion of new technologies into either commercial or military systems. Instead, it is more likely that failure will occur if a key component is missing. Common characteristics of successful technology innovators include the following: (1) the establishment of enterprises similar to Skunk Works, that is, committed multidisciplinary teams led by champions who inspire and motivate the teams toward specific goals; (2) team determination to make the technology succeed and be profitable, including convincing the customers that they need the technology; (3) mechanisms of open, free communication of knowledge and problems in meeting goals; and (4) a willingness of the champion to take personal risk, which leads to a willingness of the organization to take risks at the enterprise level. As described in detail in Chapter 1, having this organizational culture and structure in place is a necessary, but not a sufficient, condition for the successful acceleration of technology transition.

These three best practices were identified as being critical to such streamlining. While other corporate best practices are also effective at accelerating technology development and product introduction into the commercial marketplace, these three have been shown to increase the chances of success and to lower the perceived risk of failure, including personal, technical, and business risk.

Recommendation 2. The Department of Defense should adopt the following three best practices found in industry for the accelerated transition of new materials and

[14] R. Yannuzzi. 2000. In-Q-Tel: A New Partnership Between the CIA and the Private Sector. Defense Intelligence Journal, Winter. Available online at *http://www.in-q-tel.com/news/attachments/in-q-tel_cia.html*. Accessed July 2004.

technologies from concept to implementation.

- **Develop a viral process, one that is infectious and self-propagating, for technology development through the quick, iterative prototyping of materials and products, with free and open communication; agile manufacturing processes; and effective modeling of materials, processes, system performance, and cost;**
- **Work to functional requirements rather than to specifications; and**
- **Develop a flexible mechanism for creating and recreating successful teams as new systems are envisioned.**

3

Enabling Tools and Databases

The well-established success of computational engineering in various disciplines has fostered a rapid adaptation of computation-based methods to materials development in the commercial sector in recent years. Several examples are shown in Table 3.1. Early successes in computational materials engineering provide a clear vision of the way forward to enhance capabilities across the academic, industrial, and government technology developers and users. The importance of this opportunity is well recognized in recent national studies. For example:

- Acknowledging materials as one of the five critical technologies for U.S. competitiveness in the new century, the President's Office of Science and Technology Policy identified computational materials design as a principal opportunity.[1]
- In addition to emphasizing the primary importance of accelerating materials technology transition, recent studies of the National Research Council on materials and manufacturing research needs of the Department of Defense (DoD) have made computational materials design based on mechanistic models a principal recommendation for research investment.[2,3]

ESTABLISHED COMMERCIAL PRACTICE: ACCELERATED DEVELOPMENT

The aerospace original equipment manufacturer (OEM) community in particular has established a viable track record in the computation-assisted, accelerated development of materials and processes. In the environment of a modern integrated product team (IPT), the risks of materials development have been identified early in the process, and empirical materials models have been integrated with other computational tools (e.g., finite-element method) for early risk reduction and for the accelerated attainment of specific technology readiness levels (TRLs). Two specific examples presented at the workshop by Jack Schirra of Pratt & Whitney were the rapid (in 4 months) resourcing of a fan hub bonding process using available process and property models, and the rapid introduction of a new, high-temperature, high-strength shaft alloy through the integration of empirical microstructure and property models into finite-element processing models, demonstrating a three to four times reduction in time and

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[1] S.W. Popper, C.S. Wagner, and E.V. Larson. 1998. New Forces at Work: Industry Views Critical Technologies. Washington, D.C.:The Science and Technology Policy Institute of the RAND Corporation, MR-1008-OSTP.

[2] National Research Council. 2003. Materials Research to Meet 21st Century Defense Needs. Washington, D.C.: The National Academies Press, pp. 3-4.

[3] National Research Council. 2004. Retooling Manufacturing: Bridging Design, Materials, and Production. Washington, D.C.: The National Academies Press.

TABLE 3.1 Some Computational Materials Engineering Tools

Type	Tool	Company	Function
Design integration	iSIGHT	Engineous Software (Salt Lake City, Utah)	Multidisciplinary design optimization (MDO)
	CMD	QuesTek Innovations LLC (Evanston, Illinois)	Parametric materials design
Macroscopic process modeling	ProCAST	ESI Group (Paris, France)	Solidification processing
	DEFORM-HT	Scientific Forming Technologies Corporation (Columbus, Ohio)	Deformation processing and heat transfer (finite-element method)
Microstructural simulation	PrecipiCalc	QuesTek Innovations LLC (Evanston, Illinois)	High-fidelity precipitation simulation
	DICTRA	ThermoCalc AB (Stockholm, Sweden)	Multicomponent diffusion
	J MatPro	Thermotech Ltd. (Surrey, United Kingdom)	Phase relations and basic microstructural modeling
Thermodynamics	ThermoCalc	ThermoCalc AB (Stockholm, Sweden)	Multicomponent thermodynamics and phase diagrams
	Pandat	CompuTherm LLC (Madison, Wisconsin)	Multicomponent thermodynamics and phase diagrams
	FactSage	Thermfact CRCT (Montreal, Canada)	Multicomponent thermodynamics and phase diagrams

an 80 percent reduction in cost. These examples use statistically derived deterministic models to accelerate process optimization based on the behavior of mean property values.

At the workshop, Joel Clark of the International Motor Vehicle Program of the Massachusetts Institute of Technology (MIT) discussed practices that are well established for the application of technical cost modeling tools throughout the development cycle. Based in a process cycle context, these tools allow the quantitative consideration of the economic consequences of choices regarding material, process, and design, with the goal of anticipating opportunities and tactical choices at very early stages while the costs of change are still small. The tools integrate quantitative materials kinetic models to assess temperature and time trade-offs in materials process cost analysis. Such tools are broadly applied across diverse manufacturing sectors, including the automotive and optoelectronics sectors.[4]

[4] J.P. Clark, F.R. Field III, and R. Roth. 1997. Techno-economic Issues in Materials Selection. ASM Handbook, Vol. 20, Materials Selection and Design. Materials Park, Ohio: ASM International, pp. 225-265.

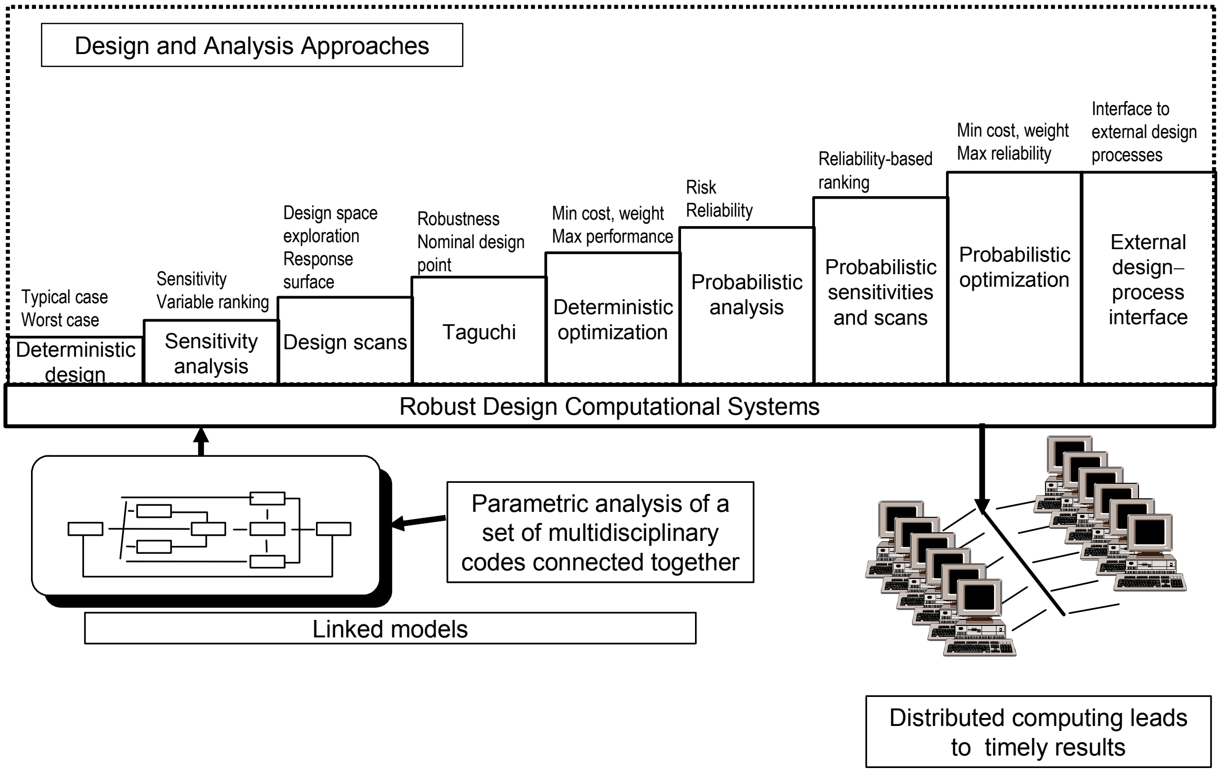


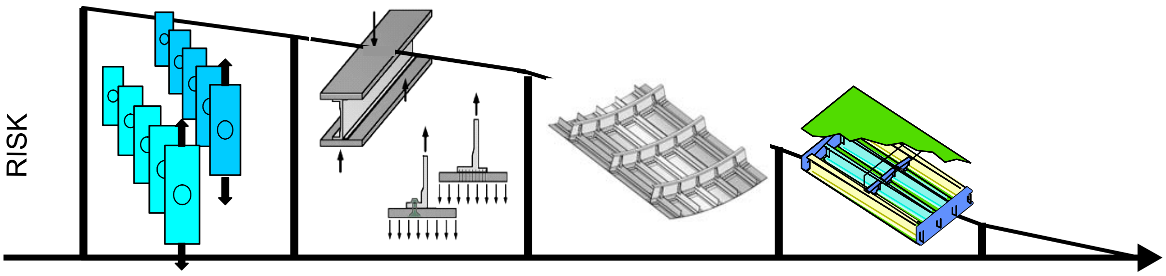
FIGURE 3.1 Range of design and analysis tools employed under the Robust Design Computational System (RDCS)—the design integration system used in the Accelerated Insertion of Materials–Composites (AIM-C) effort for the accelerated development of polymer-matrix composites. SOURCE: Copyright 2003, The Boeing Company. Used with permission.

EMERGING COMMERCIAL PRACTICE: DARPA'S ACCELERATED INSERTION OF MATERIALS PROGRAM

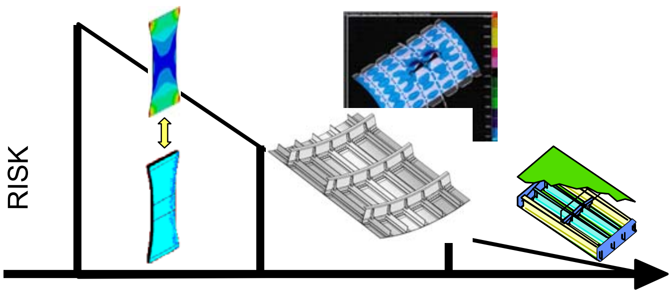
A new level of capability has very recently been demonstrated in the highly successful 2.5-year Phase I effort of the national Defense Advanced Research Projects Agency (DARPA)-AIM (Accelerated Insertion of Materials) initiative. Several presenters at the workshop described various aspects of this effort. A metals team led by Pratt & Whitney and GE Aircraft Engines and a polymer matrix composites team led by Boeing were involved in this initiative. The teams have integrated OEM, small company, university, and government laboratory activities in an IPT approach, to establish a new framework and methodology for the integration of available tools in the accelerated development and qualification of new materials and processes. The Phase I effort successfully demonstrated the ability of the methods to efficiently reconstruct both optimal processing conditions at the component level and observed property variation as established by legacy databases of existing materials; it also provided preliminary demonstrations of effective prediction of improved processing conditions for these materials.

The collaborative framework adopted by both AIM teams has employed the existing multidisciplinary design optimization (MDO) software broadly employed in systems engineering design to link diverse computational tools spanning multiple platforms and locations, efficiently integrating them with modern optimization strategies. One AIM metals team (Pratt & Whitney and GE Aircraft Engines) has employed the commercial iSIGHT design integration system, while the Boeing Accelerated Insertion of Materials-Composites (AIM-C) team has employed the Robust Design Computational System (RDCS) software. Figure 3.1 summarizes the range of capabilities of the computational systems employed in the AIM-C effort, spanning deterministic and probabilistic methods of analysis and design.

Efficient and effective integration of existing models has demonstrated a significant qualitative



(a) Traditional test supported by analysis approach.



(b) AIM provides an analysis approach supported by experience, test and demonstration.

FIGURE 3.2 Examples of materials and process development acceleration using computational tools demonstrated under the Accelerated Insertion of Materials–Composites (AIM-C) effort. SOURCE: Copyright 2003 The Boeing Company. Used with permission.

shift from an analysis-supported testing-based approach to a testing-supported analysis-based approach with an emphasis on efficient, model-driven focused testing. Figure 3.2 summarizes AIM-C demonstrations of successful model integration replacing traditional 6-month experimental efforts with 2- to 3-day modeling-based activities.

The original AIM Phase I goal was to accelerate the process of producing a traditional design knowledge base (DKB) specifying materials properties for fixed processes. A natural consequence of the new linked concurrent materials modeling capability, however, has been to create a new, active form of DKB in which the system designer can assess process and property trade-offs on the basis of estimated properties as an active part of the system design process. An example presented by Schirra at the workshop from the AIM metals program indicates that active linking of materials models to the integrated design of a subscale disk and its thermal processing accurately predicted improved performance and failure modes validated in actual disk burst tests. The timescale of the demonstration was 4 months from concept to validation.

The AIM metals effort has also demonstrated the potential predictive power of fundamentally based mechanistic models as an alternative to the more expedient statistically based empirical models commonly employed in earlier industrial efforts. This capability was achieved by the rapid concurrent development of a numerical precipitation code (PrecipiCalc) grounded in fundamental alloy thermodynamics and multicomponent diffusion. After small extensions of both a commercial thermodynamic database, Thermotech NiDATA, and a National Institute of Standards and Technology mobility database to include one additional alloying component, the mechanistic precipitation model gave highly accurate predictions of trimodal precipitate size distributions and phase compositions as functions of complex industrial thermal processing cycles in both IN100 and Rene88DT disk superalloys.

Coupled to finite-element simulations of disk heat transfer via the iSIGHT integration system, the model has given quite accurate predictions of the measured macroscopic spatial variation of precipitate

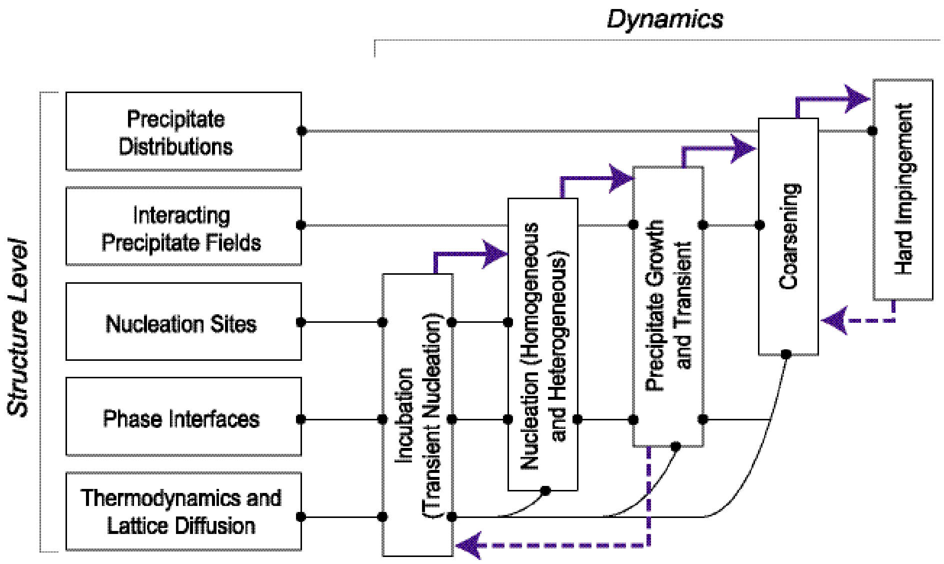


FIGURE 3.3 Schematic representation of mechanistic numerical precipitation code (PrecipiCalc) employed in Accelerated Insertion of Materials (AIM) metals demonstrations. SOURCE: C. Kuehmann, QuesTek, Tools for Design, Development and Qualification of New Materials, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24, 2003.

distributions in actual turbine disks. Linking the microstructural predictions to a structure and property model accurately predicts measured spatial variation of yield strength. The essential physical behaviors incorporated in the general-purpose precipitation code are summarized schematically in Figure 3.3. Examples of output shown include the time evolution of average precipitate size and the final size distribution. For efficiency, the numerical model is designed to compute only the microstructural parameters needed to support existing structure/property relations.

The deterministic modeling of mean behaviors has proved quite effective in the demonstration of accelerated process optimization at the component level. A major thrust of AIM research in accelerated materials qualification, however, has been the development of probabilistic modeling approaches for the reliable early prediction of DKB minimum properties, with greatly reduced reliance on test data. Adopting a mechanistic approach in which property variation is tied back to process and composition variation through predictable microstructural variation, the numerical precipitation code has served as the central transfer function allowing extensive supply-chain legacy process data to be transformed into predicted property variation under the AIM metals program. The exercise demonstrated multisite computation under the iSIGHT integration system linking distributed software capabilities in Connecticut, Utah, and Illinois; the exercise combined heat transfer, microstructure, and property calculations under a Monte Carlo simulation, incorporating known process variation as well as quantified variation in model parameters such as surface heat transfer coefficients. Computed probability distributions of yield strength at room and elevated temperatures resulted in predictions of minimum properties employing limited test data for model calibration, in good agreement with extensive legacy property data. In addition to early prediction of conventional DKB property minimums, accurate prediction of the full property probability distribution supports improved probabilistic design methods.

The industry-led DARPA-AIM team projects have provided a new clarity to the needs for computational materials engineering capability from an industrial perspective. This knowledge has already had a positive impact on allied academic research initiatives under DoD support. These notably include the Air Force Office of Scientific Research’s (AFOSR’s) Materials Engineering for Affordable New Systems (MEANS) initiative and the Office of Naval Research’s (ONR’s) Grand Challenge initiative in Naval Materials by Design. Together these foster a significant realignment of academic materials research activity to meet the computational engineering needs of a changing industry.

SMALL BUSINESS ROLE: MATERIALS BY DESIGN

Small businesses remain a vital source of technological innovation, as is evident from their supporting role in the DARPA-AIM program. The AIM program has drawn on traditional software companies serving broad industry markets, such as Engineous Software, Inc. (Salt Lake City, Utah) providing the iSIGHT design integration system and Scientific Forming Technologies Corporation (Columbus, Ohio) providing the DEFORM-HT finite-element analysis software applied in the turbine disk heat transfer simulations. In addition, the AIM effort has drawn on more recently emerging materials-centric businesses providing software products and services specific to computational materials engineering. These include QuesTek Innovations LLC (Evanston, Illinois), developers of the PrecipiCalc precipitation code; and several suppliers of materials thermodynamic software and databases including Thermotech Ltd. (Surrey, United Kingdom), CompuTherm LLC (Madison, Wisconsin), and ThermoCalc AB (TCAB) (Stockholm, Sweden).

Software products include a range of thermodynamics, multicomponent diffusion, and microstructural evolution codes supplemented by structure/property models. In addition to the PrecipiCalc code, specific software tools include the ThermoCalc (TCAB) and Pandat (CompuTherm) computational thermodynamics codes, the DICTRA (TCAB) multicomponent diffusion code, the JMatPro (Thermotech) suite of thermodynamics and simplified microstructural evolution models, and the CMD (QuesTek) materials design integration system. Available commercial services range from custom fundamental databases to full computational materials design and development on a proprietary contract basis. Commercial fundamental databases are supplemented by freeware databases distributed by NIST, representing an important new role of government laboratories in supporting this new industry.

As discussed by Charles Kuehmann of QuesTek at the workshop, small businesses may be able to support new cultures and can enable more visionary approaches than are typically possible in larger OEMs. He observed that while the DARPA-AIM initiative has focused on the later stages of development and the qualification of a material after it has been devised by traditional methods, QuesTek has implemented a broader approach for materials-by-design that builds on long-term research[5] to address the full design, development, and qualification cycle depicted in Figure 3.4.

In this approach, a broad set of tools and methods based on fundamentals are used for the rapid parametric computational design of complete materials and processes prior to making even the first laboratory prototypes. Parametric design models share a common foundation in fundamental databases and computational software to model thermodynamic and diffusion processes. These models use diffusion distance, time, and temperature constraints to provide efficient convergence to composition and process combinations. This is highly efficient compared to the more computationally intensive, explicit simulations of path-dependent time evolution of microstructure inherent in process optimization at the component level and probabilistic property modeling required in the later development and qualification stages of the materials cycle.

The incorporation of sensitivity analysis in parametric materials design allows design strategies that limit the potential for downstream property variation. The incorporation of scale effects in process models supports an approach to design for ease in processing that also reduces the risk of unanticipated scale-up problems inherent in the traditional materials-by-discovery approach. In contrast to the intensive characterization effort that was essential for the DARPA-AIM capability demonstrations on existing turbine disk alloys, the inherent predictability of materials designed this way makes them suited for more efficient accelerated development and qualification, applying the same models and validation results that created them in the first place.

As a specific example, the efficacy of computational materials design has been demonstrated with a family of high-performance gear and bearing steels designed to exploit capabilities of high-

[5] G.B. Olson. 1997. Computational Design of Hierarchically Structured Materials. Science 277 (August):1237.

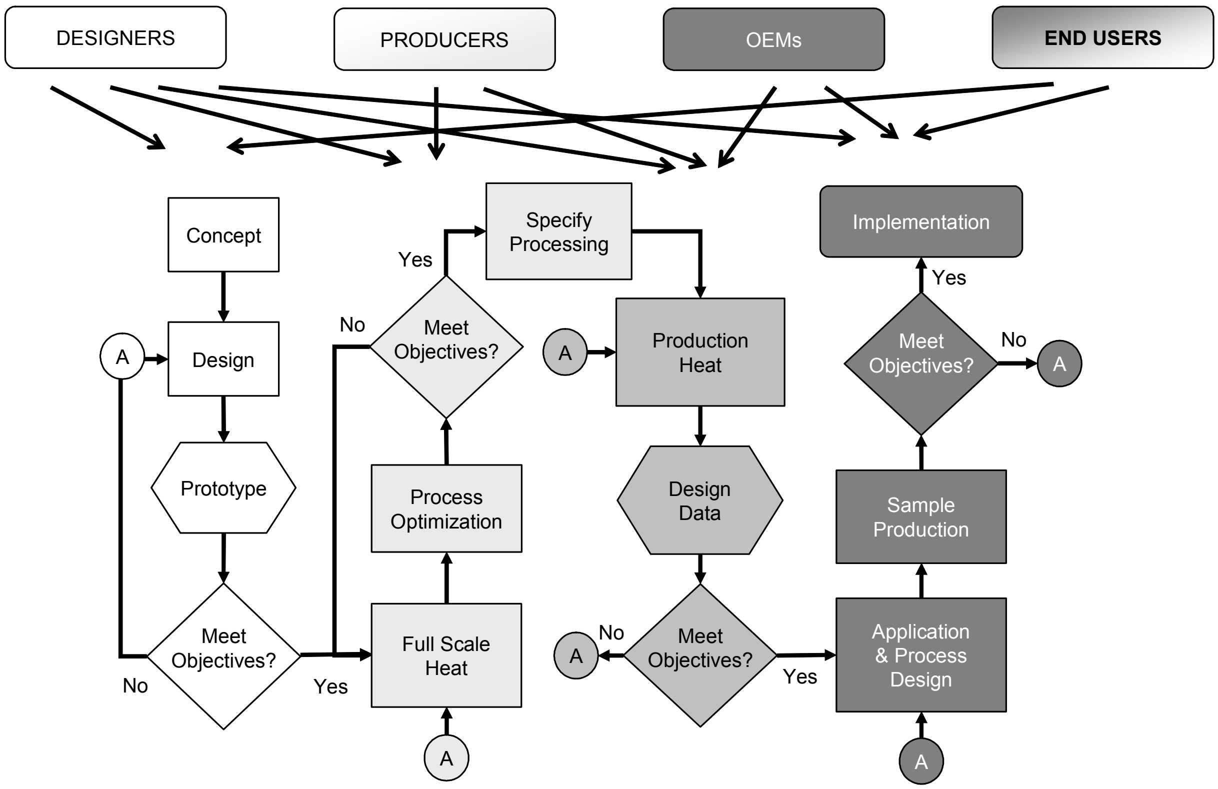


FIGURE 3.4 Flow chart of a full materials-development cycle, including initial materials design, process optimization/scale-up, and qualification testing. SOURCE: C. Kuehmann, QuesTek, Tools for Design, Development and Qualification of New Materials, briefing presented at the Workshop on Accelerating Technology Transition, National Research Council, Washington, D.C., November 24, 2003.

temperature carburizing processes.[6] Aided by process modeling based on the DICTRA multicomponent diffusion code, control of the new processing has enabled consistent achievement of new performance levels in automotive gearing, providing winning results on the racetrack, in parallel with certification testing for critical aerospace applications. These designs have spanned a range of materials, including high-performance shape memory alloys, metallic glasses, and ceramic systems.

The improved ability to predict the behavior of designed materials may also enable the expansion of the cycle to encompass the full material life cycle. Such phenomena as microstructural evolution in service may be modeled as a basis for structural health monitoring and forecasting. The inherent efficiency of design versus the traditional materials discovery approach also provides a system for affordable change in support of environmental sustainability. These methods to design materials have been used to achieve the goal of a stainless landing-gear steel, which can eliminate the need for cadmium plating. This new steel is undergoing accelerated certification testing. The project responsible for this development represents the first application of the AIM methodology to a new alloy, exploiting the full set of computational tools that created it.

In general, the AIM program has been successful at suggesting how to assemble the tools necessary to accelerate materials insertion. However, AIM methodology still needs to be transitioned into

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[6] C.E. Campbell and G.B. Olson. 2001. Systems Design of High Performance Stainless Steels: I. Conceptual Design; II. Prototype Characterization. Journal of Computer-Aided Materials Design 7:145-194; and C.J. Kuehmann and G.B. Olson. 1998. Gear Steels Designed by Computer. Advanced Materials and Processes 153(5): 40-43.

common practice, and the technology transition roadblocks identified in this report apply to it as well.

Another notable contribution of small business to the acceleration of materials technology implementation is the novel materials- and process-selection systems and supporting databases developed by firms such as Granta Design (Cambridge, United Kingdom) and Material ConneXion (New York, New York). These systems aid materials adoption by efficiently providing the information set for selection decisions from the perspective of a materials user. While Granta's Cambridge Engineering Selector system focuses on the technical needs of structural engineers, the Materials ConneXion system integrates aesthetic factors to support the broader needs of industrial designers and architects. This system also provides a natural architecture for the efficient integration of technical cost modeling in early design decisions, with the potential to support technical value analysis from a total performance perspective.

DISSEMINATION AND INFRASTRUCTURE

As an echo of the computational engineering revolution that has passed rapidly through other disciplines, the relatively recent appearance of computational materials engineering in high-tech ventures represents a new capability that is largely unknown to the majority of the materials community. An important first step in enhancing capabilities is simply that of spreading the word with respect to the tools, methods, capabilities, and achievements that already exist. An appropriate mechanism may be through ASM International—possibly in collaboration with NIST, modeled after their previous joint effort in phase diagrams. Regarding materials property data, a formal collaboration has already been established between ASM International and Granta Design to employ their selection system in the broad dissemination of new materials information.

The issues surrounding bringing modern engineering practices to such academic institutions as research universities and national laboratories has been a much-discussed issue in recent years. From the perspective of education, a series of workshops at Harvey Mudd College[7] has broadly addressed the challenges and opportunities for embedding a new design culture across all engineering disciplines including materials.[8] Under the current academic system, substantial investment in computational materials science has produced a wide array of computational tools. The majority of these, however, have so far proved to be of very limited engineering utility because they were never intended to support specific engineering needs.

Very significant exceptions are found in some materials-centered small businesses that are university spin-offs, typically founded by faculty forsaking the standard academic reward system to pursue commercially viable tools and methods meeting real needs of a new industry. In each case a productive synergy has been maintained with the parent university, which in turn enhances educational programs. A notable benchmark is the recent addition to the undergraduate materials science and engineering program at the Royal Institute of Technology in Stockholm, Sweden (originators of the widely used ThermoCalc thermodynamic software) of a degree in materials design and engineering.[9]

Wider development of technological competence in our academic institutions will require a higher level of vision from mission-oriented funding agencies. This could build on the examples of the focused

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[7] C.L. Dym, ed. 1999. Designing Design Education for the 21st Century. Proceedings, Mudd Design Workshop II, Harvey Mudd College, Claremont, Calif., May 19-21, 1999; Special Issue of International Journal of Engineering Education 17(4,5), 2001; C.L. Dym, ed. 2001. Social Dimensions of Engineering Design. Proceedings, Mudd Design Workshop III, Harvey Mudd College, Claremont, Calif., May 17-19, 2001; Special Issue of International Journal of Engineering Education 19(1), 2003; and C.L. Dym, ed. 2003. Designing Engineering Education. Proceedings, Mudd Design Workshop IV, Harvey Mudd College, Claremont, Calif., July 10-12, 2003; Special Issue of International Journal of Engineering Education 21(3), May/June 2004.

[8] G.B. Olson. 2000. Designing a New Material World. Science 288 (May): 993-998.

[9] Royal Institute of Technology in Stockholm. 2004. Curriculum in Materials Design and Engineering. Available at *http://www.kth.se/student/studiehandbok/04/lot_lista.asp?lang=1&program=BD&id=418*. Accessed July 2004.

AFOSR MEANS program, ONR Grand Challenge initiatives, and National Science Foundation centers.

A productive model may be the health-driven research system operated by the National Institutes of Health, spanning the full range from molecular biology to medicine. While the academic value system of the physical sciences has generally suppressed the creation of engineering databases, the life sciences have forged ahead with the Human Genome project representing the greatest engineering database in history. A parallel fundamental database initiative in support of computational materials engineering could build a physical science/engineering link as effective as the productive life science/medicine model. The highly successful DARPA-AIM initiative, which exposed academic participants to a well-managed IPT experience with clearly defined engineering objectives, can serve as a model for the new form of collaborative research activity enabling this needed transformation.

CONCLUSIONS AND RECOMMENDATIONS

Building on the success of computational engineering in various disciplines, rapid advances have occurred in recent decades in the adaptation of these methods to accelerated materials development in the commercial sector. While the first demonstrations have integrated empirical materials models, a new level of capability has been demonstrated very recently in the development and application of more predictive mechanistic numerical models under federally funded initiatives such as the DARPA-AIM program. Demonstrated capabilities include the following: accelerated process optimization at the component level, reducing scale-up risk; efficient, accurate forecasting of property variation to support qualification, with reduced testing for early adoption; and the active linking of materials models (exploring broader process and property trade-offs) in the higher-level system design process for the optimal exploitation of new material capabilities. Follow-on projects are actively applying the new tools and approach in the accelerated implementation of materials and processes in both polymer-matrix composites and metallic alloys for aerospace applications. Small businesses have played a vital role in these collaborative efforts. They have provided databases, tools, and methods and have expanded their capabilities to include initial parametric design of new materials, offering a unique level of predictability ideally suited to the accelerated development and qualification process.

The principal challenges and opportunities for the advancement of these capabilities concern (1) the wider dissemination of information on current capabilities and achievements, (2) the rapid transformation of the current array of academic computational materials science capabilities into useful engineering tools, (3) the broader development of necessary fundamental databases, and (4) a major infusion of modern design culture into our academic institutions to provide a pertinent research and education environment.

Recommendation 3. The Office of Science and Technology Policy should lead a national, multiagency initiative in computational materials engineering to address three broad areas: methods and tools, databases, and dissemination and infrastructure.

- *Methods and tools.* A collaboration between academia and industry built on such models as the Accelerated Insertion of Materials (AIM) program of the Defense Advanced Research Projects Agency should focus on the rapid transformation of existing, fundamental materials numerical modeling capabilities into purposeful engineering tools on a pre-competitive basis. The scope of the effort should encompass all classes of materials and the full range of materials design, development, qualification, and life cycle, while integrating economic analysis with materials- and process-selection systems.
- *Databases.* An initiative should focus on building the broad, fundamental databases necessary to support mechanistic numerical modeling of materials processing, structure, and properties. Such databases should span all classes of materials and should present the data in a standardized format. New, fundamental database assessment protocols should explore

optimal combinations of efficient experimentation and reliable first-principles calculations.

- *Dissemination and infrastructure.* A dissemination initiative should provide ready access to a Web-based source of pre-competitive databases and freeware tools as well as accurate information on the range of existing, commercial software products and services. Integrated product team-based research collaborations should be deliberately structured so as to firmly establish a modern design culture in academic institutions to provide the necessary, pertinent, research and education environment.

APPENDIXES

Appendix A

Biographical Sketches of Committee Members

Diran Apelian, *Chair*, is Howmet Professor of Engineering at Worcester Polytechnic Institute (WPI) and director of WPI's Metals Processing Institute. Dr. Apelian completed a 6-year tour of duty (1990-1996) as provost of WPI. He worked at Bethlehem Steel's Homer Research Laboratories before joining Drexel University's faculty in 1976. At Drexel he held various positions, including the following: professor, head of the Department of Materials Engineering, associate dean of the College of Engineering, and vice provost. Having joined WPI in 1990, Dr. Apelian oversees the metal-processing activities, including three consortia: metal casting, powder metallurgy, and thermal processing/heat treating. He is credited with pioneering work in various areas of solidification processing, including molten metal processing and filtration of metals, aluminum foundry engineering, plasma deposition, and spray casting and forming. Dr. Apelian received his B.S. degree in metallurgical engineering from Drexel University and his Sc.D. in materials science and engineering from the Massachusetts Institute of Technology (MIT). He is the recipient of many distinguished honors and awards, including honorary membership in the French Metallurgical Society; an honorary doctorate from Northwestern Polytechnic University in Xian, China; the Champion H. Mathewson Gold Medal; the Howe Medal; and the Howard Taylor Gold Medal. Dr. Apelian has more than 380 publications to his credit and serves on several technical and corporate boards.

Andrew Alleyne is the Ralph M. and Catherine V. Fisher Professor of Engineering in the Department of Mechanical and Industrial Engineering at the University of Illinois in Urbana-Champaign (UIUC). He is also an associate professor at the Coordinated Science Laboratory. His research interests focus on the modeling, analysis, and control of mechanical systems with an emphasis on automotive and manufacturing systems. Dr. Alleyne has also been a visiting professor of vehicle mechatronics in the Faculty of Design, Engineering, and Production at Delft University of Technology, The Netherlands; a faculty fellow at Caterpillar, Inc.; a faculty fellow at the Ford Motor Company; a member of the research staff at the Jet Propulsion Laboratory; and an engineer in the Rochester Products Division of General Motors. Dr. Alleyne graduated magna cum laude from Princeton University with a B.S.E. in Aerospace Engineering. He received his M.S. and Ph.D. degrees from the University of California at Berkeley's Mechanical Engineering Department. He has several honors and publications, including the Society of Automotive Engineers Ralph R. Teetor Educational Award; the Xerox Award for Faculty Research; a National Science Foundation (NSF) Faculty Early Development (CAREER) Award; the Princeton University Raymond S. Greenlea Award; the Accenture Award for Excellence in Advising at the UIUC College of Engineering; and the Engineering Council Award for Excellence in Advising at the UIUC

College of Engineering.

Carol A. Handwerker is chief of the Metallurgy Division at the National Institute of Standards and Technology. Her expertise is in the area of materials and processes development. Dr. Handwerker joined the National Bureau of Standards (NBS) in 1984 as a National Research Council postdoctoral research associate, working on the relationship between stress and diffusion in solids and on composition effects on sintering and grain growth. Her research has focused on the thermodynamics and kinetics of interface processes, with applications to electronic packaging, composites, reactive wetting, sintering, and grain growth. Dr. Handwerker received a B.A. in art history from Wellesley College; she then went on to receive a B.S. in materials science and engineering and an M.S. and an Sc.D. degree in ceramics from MIT. She was awarded the Department of Commerce Bronze Medal for her contributions to the understanding of interface reactions in composites, the Department of Commerce Silver Medal for her contributions to solder science, and the Richard Fulrath Award from the Northern California Section of the American Ceramic Society. Dr. Handwerker is a fellow of the American Society for Metals International, and the American Ceramic Society (ACerS), and she is past chair of the ACerS Basic Science Division. She is on the Technical Advisory Committee for National Electronics Manufacturing Initiative, the board of trustees of the Gordon Research Conferences, the Visiting Committee for the MIT Department of Materials Science and Engineering, the Advisory Committee of Carnegie Mellon University's Mesoscale Interface Mapping Project, the editorial board for the *Annual Reviews of Materials Research*, and several governmental advisory groups. She has authored more than 80 scientific publications.

Deborah Hopkins is a staff scientist at the Lawrence Berkeley National Laboratory, where she heads the Engineering Division’s Technology Transfer and Industry Partnerships Group. She also leads a multidisciplinary research team working on the collaborative research and development with industry partners. Her current projects include the development of an ultrasonic phased-array system for the inspection of spot welds and the development and analysis of thermal insulation and window technologies, in collaboration with partners in the automotive industry; the development of technologies for rock characterization during drilling, in collaboration with partners in the mining industry; and the development of cooling strategies for optoelectronic components, in collaboration with partners in the telecommunications industry. Dr. Hopkins is an active participant in several international research collaborations and has recently served as a visiting professor at the University of Bordeaux, France, where her analytical models are being used to study the hydromechanical behavior of natural rock fractures on the basis of data from French laboratory and field experiments. She has twice served as a visiting scholar at the Bureau de Recherches Géologiques et Minières in France doing similar work. As a visiting professor at the Technical University of Lund, Sweden, in 1996, Dr. Hopkins taught a graduate course on statistical methods and performed research on the role of public policy in fostering technological advancements for the development of cleaner, more fuel-efficient automobiles. Dr. Hopkins holds a B.S. double major in mathematics and environmental economics and a secondary teaching credential in mathematics and social studies from the University of Washington, Seattle; she also received an M.A. in statistics and a Ph.D. in materials science and mineral engineering from the University of California at Berkeley. She has published numerous papers on the subjects of nondestructive evaluation and the mechanical and acoustic behavior of fractures and joints.

Jacqueline A. Isaacs is an associate professor in the Department of Mechanical, Industrial, and Manufacturing Engineering at Northeastern University. Her research areas include environmentally benign manufacturing, competitive economic and environmental analyses of alternative materials throughout the product life cycle, modeling tools developed and applied to various competing manufacturing methods, and analysis of end-of-life disposal strategies for automobiles with policy repercussions. Her past positions were as assistant professor in the Department of Mechanical, Industrial, and Manufacturing Engineering at Northeastern University; the director of environmental programs in the Materials Systems Laboratory at MIT; and a research engineer at the Aluminium Research Laboratories in Ranshofen, Austria. Dr. Isaacs holds a B.S. in metallurgical engineering and materials science from Carnegie Mellon University, and an M.S. and Ph.D. in materials science and engineering from MIT. She has several honors and publications, including the Bright Idea Award from the Professional Organizational and Development Network in Higher Education competition for supporting faculty development, the Northeastern University Excellence in Teaching Award, and the NSF CAREER Development Award.

Gregory B. Olson is the Wilson-Cook Chaired Professor in Engineering Design in the Department of Materials Science and Engineering at Northwestern University. The aim of his research is to approach at the most fundamental level possible those classical problems of physical metallurgy that remain of central importance to materials science and engineering. Directed at phenomena of broad relevance to materials, Dr. Olson's research is often focused on steels as a unique class of materials whose vast database allows a sophistication of approach not feasible in any other material. His current research areas include the following: a general kinematic theory of interphase boundary structure, the mechanism and kinetics of coupled diffusional and displacive transformations, the electronic basis of embrittlement mechanisms in metals, the design of new steels from first principles, and new applications of materials science to molecular biology. His research seeks to strengthen and expand the paradigms that can identify materials science as a viable discipline, while incorporating usable developments in the related fields of physics and chemistry. A major thrust of Dr. Olson's current research centers on a university-government-industry program coordinating 30 investigators on high-strength steel technology, which aspires to improve the science-based engineering of materials. His future research and teaching interests lie in a synthesis of theory of phase transformations and mechanical behavior to develop a general kinetic theory of microstructural evolution applicable to both structure control and micromechanical processes in structural materials, and the incorporation of systems analysis concepts. Dr. Olson received his B.S., M.S., and Sc.D. degrees in materials engineering from MIT. He has several honors, patents, and publications. His honors include being named a fellow of the Minerals, Metals and Materials Society and a fellow of ASM International. He has also received a number of awards, including an AMAX Foundation fellowship, an NSF Creativity Extension Award, the Army Materials Technology Laboratory Special Service Award, the Jacob Wallenberg Foundation Award (Sweden), the M.R. Tenenbaum Award from the Iron and Steel Society, and a National Aeronautics and Space Administration (NASA) Technology Recognition Award. He has also been an Alpha Sigma Mu lecturer for ASM International.

Ranji Vaidyanathan is manager of Advanced Materials at Advanced Ceramics Research, Inc. His major area of expertise is that of accelerated product development techniques for functional metal, ceramic, and composite parts. His product development achievements include water-soluble tooling materials for polymer composite fabrication of environmentally friendly products, generating about $100,000 in sales in one year from sales in the United States, Europe, and Japan; Osteoceram (Plasti-Bone), a biocompatible tissue engineering material developed to replace the current set of bone replacement materials, which can be custom-fabricated from computer-aided design models; and an in situ foaming technique for metal foam components, which can be fabricated directly from computer models. Dr. Vaidyanathan's other research interests include solid freeform fabrication of polymers, ceramics, metals, and composites; rheology; fracture mechanics, life-prediction using analytical modeling; and tissue engineering using polymer- and ceramic-matrix composites. He has also been an adjunct associate professor in the Department of Aerospace and Mechanical Engineering of the University of Arizona; a senior research scientist at the Materials and Electrochemical Research Corporation; a research fellow in the Department of Mechanical Engineering at Johns Hopkins University; a research associate in the Center for Ceramic Research at Rutgers University; and a research associate in the Department of Mechanical Engineering of the North Carolina Agricultural and Technical State University. Dr. Vaidyanathan has a B.S. in metallurgical engineering from Banaras Hindu University, India; an M.S.M.E in mechanical engineering and a Ph.D. in materials science and engineering from the North Carolina State University. He has several honors, patents, and publications, including the R&D 100 Award in 2001 for developing water-soluble tooling materials for the fabrication of polymer matrix composite articles.

Sandra DeVincent Wolf is an expert in the area of materials characterization and performance. She has worked on a number of projects in this area, beginning with the development of a gas tungsten arc welding process and on the characterization of weldment properties of aluminum armor alloys at the U.S. Army Materials Technology Center in Watertown, Massachusetts. She was a National Research Council fellow at the NASA Lewis Research Center, Cleveland, Ohio, where her research focused on the development of graphite-fiber-reinforced copper composites, including alloy wetting studies and diffusion modeling, pressure infiltration casting of graphite/copper composites, and thermal and mechanical characterization of those composites. As manager of R&D at PCC Composites, Inc., Dr. Wolf was responsible for overseeing the development and characterization of various silicon carbide-reinforced aluminum alloy composites. She joined Westinghouse Plant Apparatus Division (later Bechtel Plant Machinery, Inc.) in 1996 and was responsible for the specification, procurement, and qualification of automated welding and cutting equipment. In addition, she led a team to design reusable mock-ups for testing the welding and cutting equipment and to develop the production procedures and technical manuals necessary to utilize that equipment. Dr. Wolf has a B.S. in materials science and engineering from MIT and an M.S. and Ph.D. in materials science and engineering from Case Western Reserve University. She has published numerous papers, particularly in the area of fabrication, characterization, and performance of composite materials. She is an active member of ASM International and is currently a member of its Materials Solutions Exhibition Committee, a member of its Technical Programming Board, chair of the ASM's Primary Metals Sector, and treasurer of the ASM Pittsburgh Chapter. She has been active in various roles in both the Cleveland and Pittsburgh Chapters of ASM and was recognized as the ASM Pittsburgh Chapter Outstanding Young Member in 1999 as well as receiving the President's Award in 2004.

Appendix B

Workshop Agenda

WORKSHOP ON ACCELERATING TECHNOLOGY TRANSITION

November 24-25, 2003

National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C.

MONDAY, NOVEMBER 24

8:30 a.m. Welcome and Remarks, *Diran Apelian, Worcester Polytechnic Institute, and Chair, Workshop Committee*

Session 1: Technology Transition Overviews

Session Co-Chairs: William Coblenz, Defense Advanced Research Projects Agency (DARPA), and Deborah Hopkins, Lawrence Berkeley National Laboratory

8:45 a.m. Military Needs for Technology Transition, *General Alfred M. Gray, U.S. Marine Corps (retired)*

9:00 a.m. Navy Needs for Technology Transition, *Michael F. McGrath, U.S. Navy*

9:15 a.m. Technology Transition in Aerospace Industry, *Robert Schafrik, GE Aircraft Engines*

9:30 a.m. Technology Transition from Small Business Industry, *Joseph Tippens, Universal Chemical Technologies, Inc.*

9:45 a.m. Panel Discussion

Session 2: Integrated Design and Manufacturing Groups—Case Studies

Session Co-Chairs: Alan Miller, Boeing Commercial Airplane Group, and Ranji Vaidyanathan, Advanced Ceramics Research, Inc.

10:30 a.m. Boeing Phantom Works, *David Banks, The Boeing Company*

10:45 a.m. Lockheed Martin Skunk Works, *Ned Allen, Lockheed Martin Aeronautics Company*

11:00 a.m. Uninhabited Air Vehicles and Fibrous Monolith Technology, *Anthony Mulligan, Advanced Ceramics Research, Inc.*

11:15 a.m. America's Cup Technologies, *Dirk Kramers, Team Alinghi SA*

11:30 a.m. Formula 1 Race Car Technologies, *Mark Taylor, Office of Naval Research*

11:45 a.m. Panel Discussion

Session 3: Computational and Collaborative Tools—Lessons Learned

Session Co-Chairs: Gregory B. Olson, Northwestern University, and Sandra DeVincent Wolf, Consultant

1:30 p.m. Tools for Metallic Materials, *Jack Schirra, Pratt & Whitney*

1:45 p.m. Tools for Composite Materials, *Gail Hahn, The Boeing Company*

2:00 p.m. Tools for Design, Development, and Qualification of New Materials, *Charles Kuehmann, QuesTek Innovations LLC*

2:15 p.m. Technical Cost Modeling Tools, *Joel Clark, International Motor Vehicle Program, Massachusetts Institute of Technology*

2:30 p.m. Panel Discussion

Session 4: Design and Validation Methodologies—Lessons Learned

Session Co-Chairs: Bruce Fink, Army Research Laboratory, and Carol Handwerker, National Institute of Standards and Technology

3:15 p.m. Single Process Initiative for Technology Change in Existing Military Systems; *Joseph R. Felty, Raytheon Systems Company*

3:30 p.m. Accelerated Insertion of AerMet 100 into F-18 Landing Gears, *K.K. Sankaran, The Boeing Company*

3:45 p.m. Lessons from Kinetic Energy Tank Projectile Applications, *Christopher Hoppel, Army Research Laboratory*

4:00 p.m. Panel Discussion

4:30 p.m. Day 1 Closing Remarks

TUESDAY, NOVEMBER 25

Session 5: Approaches and Tools for Accelerated Technology Transition

Session Co-Chairs: Andrew Alleyne, University of Illinois, and Diran Apelian, Worcester Polytechnic Institute

8:00 a.m. Technology Transition Approaches at Moog, *Richard Aubrecht, Moog, Inc.*

8:15 a.m. Technology Transition in the Automotive Industry, *Charles Wu, Ford Motor Company*

8:30 a.m. Technology Transition Approaches at 3M, *Rich Bushman, 3M*

8:45 a.m. Approaches Used for Deployment of Automated Biological Detection Systems, *David Tilles, Northrop Grumman Automation and Information Systems*

9:00 a.m. Panel Discussion

Session 6: Lessons Learned from Other Industries

Session Co-Chairs: Jacqueline Isaacs, Northeastern University, and Diran Apelian, Worcester Polytechnic Institute

9:45 a.m. Medical Products Industry, *Art Coury, Genzyme Corporation*

10:00 a.m. Metal Casting Industry, *Paul Mikkola, Metal Casting Technology, Inc.*

10:15 a .m. Environmental Industry, *Arthur Rogers, Environmental Sciences, Inc., and Steve Johnson, Concurrent Technologies Corporation*

10:30 a.m. Panel Discussion

Session 7: Summary Session

Session Co-Chairs: Diran Apelian, Worcester Polytechnic Institute, and Gregory B. Olson, Northwestern University

11:00 a.m. Summary of Session 1: Technology Transition Overviews, *Deborah Hopkins, Lawrence Berkeley National Laboratory*

11:10 a.m. Summary of Session 2: Integrated Design and Manufacturing Groups, *Alan Miller, Boeing Commercial Airplane Group, and Ranji Vaidyanathan, Advanced Ceramics Research*

11:20 a.m. Summary of Session 3: Computational and Collaborative Tools, *Gregory B. Olson, Northwestern University, and Sandra DeVincent Wolf, Consultant*

11:30 a.m. Summary of Session 4: Design and Validation Methodologies, *Carol Handwerker, National Institute of Standards and Technology*

11:40 a.m. Summary of Session 5: Approaches and Tools for Accelerated Technology Transition, *Andrew Alleyne, University of Illinois, and Diran Apelian, Worcester Polytechnic Institute*

11:50 a.m. Summary of Session 6: Lessons Learned from Other Industries, *Jacqueline Isaacs, Northeastern University, and Diran Apelian, Worcester Polytechnic Institute*

12:00 p .m. Closing Remarks

12:15 p.m. Adjourn

Appendix C

Acronyms

AIM	Accelerated Insertion of Materials
AIM-C	Accelerated Insertion of Materials–Composites
DARPA	Defense Advanced Research Projects Agency
DKB	design knowledge base
DoD	Department of Defense
IPT	integrated product team
MDO	multidisciplinary design optimization
MIT	Massachusetts Institute of Technology
NIST	National Institute of Standards and Technology
OEM	original equipment manufacturer
PARC	Palo Alto Research Center
RD	Robust Design Computational System
RDTE	research, development, testing, and evaluation
TRL	technology readiness level
R&D	research and development