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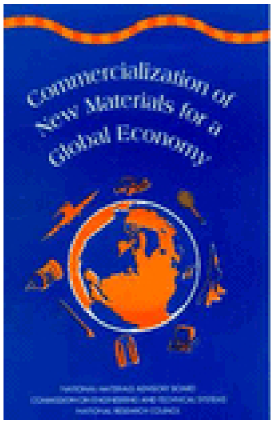

Commercialization of New Materials for a Global Economy

Commission on Engineering and Technical Systems, National Research Council

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

Commercialization of New Materials for a Global Economy

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

NMAB-465

National Academy Press
1993

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

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Abstract

Materials are important in the pursuit of virtually every human endeavor. Advances in materials are applied not only in advanced technological systems such as spacecraft, jet engines, computers, and telecommunications but also in a world of familiar applications, from automobiles to floor coverings to fishing rods. Materials are an enabling technology—that is, each improvement in materials increases the possibility for advances in other fields of technology. Based on a synthesis of a 3-day workshop that featured presentations by National Materials Advisory Board members and case studies by invited representatives from four materials suppliers, this report addresses the factors that impede the transition of new materials from concept into commercial use. It suggests action-oriented strategies that government and industry, together with universities, can take to remove these impediments.

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Preface

This report is the result of a request by the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) for the National Materials Advisory Board (NMAB) to examine the process by which U.S. industry brings new materials to market and to suggest ways to promote more rapid commercialization of promising new materials and processes. The agencies have two reasons for such an interest:

1. Rapid and frequent commercial production of new materials in larger volume would allow DOD and NASA contractors to build more-capable advanced systems at lower life-cycle cost.
2. The nation invests substantial resources in the pursuit of national security and leadership in space. Yet the results of this materials research and development (R&D) often do not find their way readily into the civilian economy. Rapid commercial availability of new materials would permit their incorporation into products and thereby enhance the global competitiveness of U.S. manufacturing industries.

The NMAB held a 3-day workshop to examine these issues. The workshop was held October 28–30, 1990, at the Beckman Center of the National Academy of Sciences in Irvine, California.

Four speakers were invited to the workshop to present specific case studies. Mr. Paul R. Langston, Senior Program Manager at DuPont, presented the development of Kevlar™ fiber; Dr. David M. Schuster, Vice President, Duralcan USA, presented the development of a metal-matrix composite: aluminum reinforced with ceramic particles; Dr. John P. Riggs, Vice President, Hoechst Celanese Corporation, and a member of the NMAB, presented the development of carbon-fiber composites; and Mr. C. K. Mullen, Vice President, BP Chemicals (HITCO) Incorporated, presented the development of carbon-carbon composites.

Presentation and discussion of these case studies formed the basis of a plenary session that was in turn followed by four parallel workshop sessions on design and manufacturing issues, component materials issues, institutional and policy issues, and market factor issues. These were followed by a final session to crystallize the findings of the group and to discuss strategies on how to overcome barriers to commercialization. A small editorial committee met on three separate occasions following the workshop, and final discussions were held at two subsequent NMAB meetings. The authors of the report are the board members listed on pages v–vii.

It quickly became evident in the workshop that the factors impeding commercialization involve not only technical barriers but also legal/regulatory and economic barriers. Although the expertise of the members of the NMAB and invited guests was primarily in the technical arena, all barriers to commercialization were discussed. General strategies to overcome these barriers were synthesized, with the recommendation that they be further explored by other groups possessing a balance of current, detailed knowledge of all factors associated with these barriers. Follow-on studies could draw on these strategies as a starting point in formulating specific recommendations.

The NMAB hopes that the report and the strategies it presents will provide useful guidance to government, industry, and universities as they deal with this timely and important issue for the nation.

Any comments or suggestions that readers of this report wish to make can be sent via Internet electronic mail to nmab@nas.edu or by fax to NMAB at (202) 334-3718.

JAMES C. WILLIAMS

CHAIRMAN

Acknowledgements

The National Materials Advisory Board (NMAB) would like to express its appreciation to the many participants who attended the workshop. The NMAB would also like to thank the speakers who presented specific case studies at the workshop: Mr. Paul R. Langston, Senior Program Manager at DuPont; Dr. David M. Schuster, Vice President, Duralcan USA; Dr. John P. Riggs, Vice President, Hoechst Celanese Corporation; and Mr. C. K. Mullen, Vice President, BP Chemicals (HITCO) Incorporated. The NMAB is also grateful to the following individuals who assisted with the early drafting of the report: Cathryn Summers, Project Assistant; Mary W. Brittain, Administrative Assistant; and Courtland S. Lewis, Technical Writer.

THE NATIONAL ACADEMIES

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The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institutedicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

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Contents

COMMERCIALIZATION OF NEW MATERIALS FOR A GLOBAL ECONOMY

Executive Summary

The importance of materials as an *enabling technology* has been increasingly acknowledged during the past several decades. For instance, advances in materials have contributed to the success of advanced technological systems such as spacecraft, jet engines, computers, and telecommunications. New materials have also contributed to familiar consumer applications that range from automobiles to refrigerators to tennis racquets and fishing rods.

The United States has been most successful in the laboratory invention of new technologies including materials, but it has not always been as successful as other industrialized nations in the commercialization of such technologies. This study had its origin in the concern of the Department of Defense (DOD) and National Aeronautics and Space Administration (NASA) that advanced materials are not being commercialized fast enough to build more-capable advanced systems at lower life-cycle cost. In addition, it was recognized that rapid commercial introduction of new materials and their incorporation into products would enhance the global competitiveness of the United States (FCCSET, 1992).

The members of the National Materials Advisory Board (NMAB) and invited guests held a workshop to examine the barriers to commercialization of materials. The factors that were judged to affect commercialization were analyzed and synthesized. They were divided into three groups: technical, regulatory/legal, and economic. The members of the NMAB then developed a series of broad strategies that addressed the primary barriers to commercialization. These strategies are grouped below by lead organization.

FEDERAL GOVERNMENT

- The commercialization process would benefit from timely, wide dissemination of materials research and development (R&D) information. The federal government could establish a clearinghouse activity, containing relevant aspects of all federally funded materials programs that span the range from basic research through pilot production, to serve as a single source of readily available information. The information would describe the materials being developed and commercialized under federal sponsorship, funding levels, milestones, and so on. Such a data base would allow better coordination among all federally funded materials efforts, resulting in reinforcing, comprehensive efforts. For example, it would facilitate the identification of program gaps and overlap areas. Industry and academia would have access to the "big picture" and thus be able to anticipate when materials of interest would be available for use. In addition, industry could be asked to assess the commercialization potential of specific development efforts, taken as a whole; appropriate changes could then be made early enough to ensure that commercialization would not be delayed due to an oversight.
- Future commercial applications of advanced materials will almost always include potential markets beyond initial government applications. These applications are very important, because they add to the commercial potential of new materials. To provide as broad an application window as possible, the government materials R&D program could incorporate along with the known government requirements, or otherwise address, the key material needs for leading commercial applications. Appropriate mechanisms to discover and assess these needs would have to be established as well.
- Export control regulations can limit the use of advanced materials technology, often without apparent meaningful purpose. Current regulations can unnecessarily interfere with the interactions between U.S. firms and their foreign partners. This restricts the broadening of the U.S. technical base and limits U.S. firms' access to

overseas markets. A study by the National Research Council Committee on Science, Engineering, and Public Policy recommended that the basis of technology transfer restrictions be changed from a policy of general denial of dual-use items to a policy of presumed approval for export, based on verified end-use of the product (COSEPUP, 1991). This recommendation could be used as a framework to address the necessary changes to the export control regulations.

- Economic and legal barriers to, as well as financial incentives for, the commercialization of materials are continually undergoing change. For instance, tax incentives, government procurement policies, and intellectual property-protection clauses are the subject of numerous legislative actions and judicial decisions within the course of a year. These areas could be examined in detail by appropriate experts to determine what changes could prudently be made to assist in accelerating the commercialization process.

INDUSTRY

- Focused, cooperative, cost-shared efforts can speed the commercialization of materials through such activities as precompetitive R&D, demonstration of process reproducibility, application development, development of design data bases, and joint-use capital facilities. Industry could establish consortia that include materials suppliers, part fabricators, and end users. As appropriate, the expertise and unique facilities of the federal laboratories can be integrated into such consortia.
- Materials suppliers typically provide their products to makers of semi-finished products, such as forging and casting houses. This tends to decouple material companies from their ultimate customers: the end users. Direct links between the materials suppliers and the end users would provide the materials industry with first-hand knowledge of user needs, and the users with first-hand appreciation

of capabilities within the materials industry. An informal interactive forum, implemented on an individual basis and an industry-wide basis, could allow the necessary interchange of information and improve market pull and product focus for materials producers. Existing mechanisms already in place at various trade associations can facilitate these interactions. Use of video conferencing electronic communications would further reduce the cost of maintaining the forum.

- Revolutionary new materials generally can fulfill their complete potential only if new design methods are applied to new products. The consequence is that advanced materials often wait "on the shelf" until new markets develop. However, the insertion of improved materials to incrementally improve existing products can be an attractive way to use an existing market to build demand for an advanced material, even though it may not exploit the material to its fullest capability. This product improvement strategy requires an updating of product design approaches to reflect the unique aspects of the new material. Consideration must also be given to any environmental and use changes that the product might experience as a result of added capability.

UNIVERSITIES

- The education of engineering students includes instruction on design methods for specific applications and on the selection of materials based on properties that can be affected by processing history. Introducing advanced materials into the educational process requires associated instruction on revised, or entirely new, design approaches and methods to allow full exploitation of the featured properties, avoidance of failure modes, and so on. A partnership of university, industry, and government could be used to develop realistic ways to encourage and support these necessary changes within the educational system. For example, the "practice school" model could be extended to include materials processing and manufacturing education.

- Advanced materials technology often eclipses the experience and knowledge base of practicing design engineers and manufacturing engineers. Continuing education programs for experienced practitioners could be an effective mechanism for bringing them up to date, providing a necessary knowledge base and expert tutelage. As a result, experienced professionals would be able to resynthesize their conventional designs in line with useful new paradigms.
- Technical personnel without degrees perform many crucial tasks throughout engineering and manufacturing. Their experience base is derived largely from learning successful procedures. Thus, practice-oriented training programs in areas involving advanced materials could extend their experience base. This approach could significantly reduce the number of problems associated with the introduction of new materials. Such a strategy might take advantage of programs offered by various technical societies.

ALL SECTORS WORKING TOGETHER

- Development of materials standards, including international standards, is an essential aspect of building the infrastructure needed to support the commercialization of advanced materials. A federal agency, such as the National Institute of Standards and Technology, could establish a forum to develop the standards through timely, active participation by industry and other interested parties.
- Greater standardization of design-related, materials-property data bases is necessary to facilitate the widespread application of new materials and thus increase the size and number of potential markets. The materials industry could lead this effort, with

wide participation by government, universities, and professional societies.

1—

Introduction

Materials are important in the pursuit of virtually every human endeavor. Advances in materials are applied not only in advanced technological systems such as spacecraft, jet engines, computers, and telecommunications but also in a world of familiar applications that range from automobiles to floor coverings to fishing rods. Thus, materials are an enabling technology—that is, each improvement in materials increases the possibility for advancements in other fields of technology.

In a National Research Council study, *Materials Science and Engineering for the 1990s*, a detailed examination of the role of materials in eight U.S. industries that collectively employ more than 7 million people and have sales in excess of $1.4 trillion led to the conclusion that "materials science and engineering is crucial to the success of industries that are important to the strength of the U.S. economy and U.S. defense" (NRC, 1989). Yet, as is widely known, the competitiveness of some U.S. manufacturing industries has declined alarmingly. For example, in 1972 the United States imported 14.8 percent of its automobiles (ORNL, 1991); by 1991 imports had increased to over 25 percent. In 1991, an additional 11 percent were foreign cars manufactured in the United States, and many of the remaining 64 percent had foreign content (ORNL, 1990; MVMA, 1991).

A previous report by the National Academy of Engineering stated the issue succinctly: "Rapid and efficient commercial embodiment of an idea in a product or service is an essential element of successful international competition" (NAE, 1988).

For instance, the commercial aircraft industry was able to be established in the United States in the 1950s partly because there already was a domestic aluminum industry. A strong aluminum industry enabled the rapid development of supersonic and commercial aircraft following World War II. Today the annual value of U.S. exports in commercial airframes is $44 billion. There presently is a trend toward the greater use of composite materials in airframes. As was earlier the case with aluminum, these materials are likely to be the foundation of the next generation of aircraft. Thus, the United States cannot afford to lose its momentum commercializing such important advanced materials as composites.

Several recent studies dealing with the competitive position of the United States were summarized by the Office of Science and Technology Policy (OSTP, 1991). Emerging or critical technologies have been identified by that office and by the Department of Commerce and the Department of Defense (DOC, 1990; DOD, 1990); the comparison is shown in Table 1-1. Advanced materials, synthesis and processing of materials, and manufacturing are emphasized in each of the case studies. Almost identical conclusions from these independently conducted studies lend credence to the widely held belief that materials are indeed a critical enabling technology.

The following chapters deal with definitions of advanced materials, the commercialization process, and the government's stake in it (Chapter 2); the factors that affect commercialization of materials (Chapter 3); and strategies for overcoming commercialization barriers (Chapter 4).

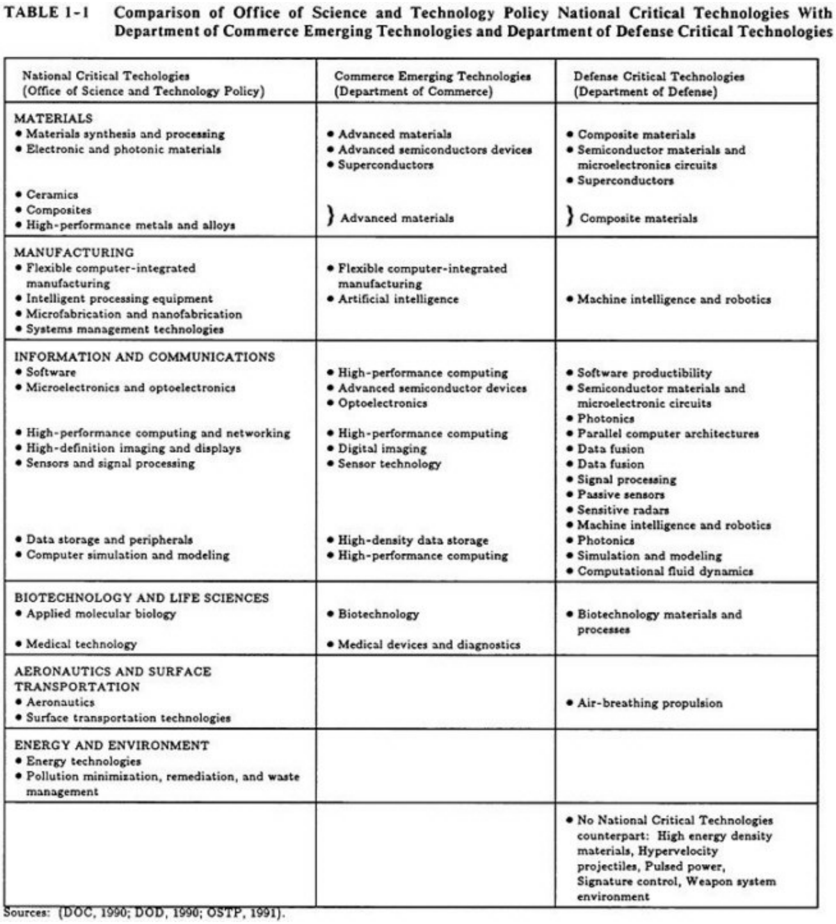


TABLE 1-1 Comparison of Office of Science and Technology Policy National Critical Technologies With Department of Commerce Emerging Technologies and Department of Defense Critical Technologies

National Critical Techologies (Office of Science and Technology Policy)	Commerce Emerging Technologies (Department of Commerce)	Defense Critical Technologies (Department of Defense)
MATERIALS • Materials synthesis and processing • Electronic and photonic materials	• Advanced materials • Advanced semiconductors devices • Superconductors	• Composite materials • Semiconductor materials and microelectronics circuits • Superconductors
• Ceramics • Composites • High-performance metals and alloys	} Advanced materials	} Composite materials
MANUFACTURING • Flexible computer-integrated manufacturing • Intelligent processing equipment • Microfabrication and nanofabrication • Systems management technologies	• Flexible computer-integrated manufacturing • Artificial intelligence	• Machine intelligence and robotics
INFORMATION AND COMMUNICATIONS • Software • Microelectronics and optoelectronics	• High-performance computing • Advanced semiconductor devices • Optoelectronics	• Software productibility • Semiconductor materials and microelectronic circuits • Photonics
• High-performance computing and networking • High-definition imaging and displays • Sensors and signal processing	• High-performance computing • Digital imaging • Sensor technology	• Parallel computer architectures • Data fusion • Data fusion • Signal processing • Passive sensors • Sensitive radars • Machine intelligence and robotics
• Data storage and peripherals • Computer simulation and modeling	• High-density data storage • High-performance computing	• Photonics • Simulation and modeling • Computational fluid dynamics
BIOTECHNOLOGY AND LIFE SCIENCES • Applied molecular biology	• Biotechnology	• Biotechnology materials and processes
• Medical technology	• Medical devices and diagnostics	
AERONAUTICS AND SURFACE TRANSPORTATION • Aeronautics • Surface transportation technologies		• Air-breathing propulsion
ENERGY AND ENVIRONMENT • Energy technologies • Pollution minimization, remediation, and waste management		
		• No National Critical Technologies counterpart: High energy density materials, Hypervelocity projectiles, Pulsed power, Signature control, Weapon system environment

Sources: (DOC, 1990; DOD, 1990; OSTP, 1991).

2—

New Materials and their Commercialization

DEFINITION OF ADVANCED MATERIALS

The term *advanced materials* encompasses a wide range—from composites with very high strength/weight ratios to silicon wafers with feature sizes approaching atomic dimensions. For example, metal-matrix composites are combinations of materials possessing unprecedented strength/weight ratios and requiring entirely novel processing. In addition, advanced materials can have unique combinations of properties (e.g., high strength combined with a specific coefficient of expansion), or they can be tailored to a specific requirement (e.g., graded seals).

One of the best, concise definitions of "advanced materials" is given in the Advanced Materials and Processing Program plan (AMPP), a document that supplemented the President's budget submission for fiscal year 1993 (FCCSET, 1992). The report states that ". . . advanced means the most recent evolutionary developments within a materials class . . . " The meaning of *advanced* thus encompasses traditional materials that have been improved as well as new materials recently invented. A few specific examples given by the workshop participants include materials that exhibit:

- *unprecedented composition*, such as $YBa_2Cu_3O_7$, a high-temperature superconducting ceramic;
- *unusual purity*, such as silica-based optical fibers for optical communication;

- *novel structure and/or combinations*, such as carbon fiber-reinforced thermoplastic polymeric composites;
- *novel processing*, such as molecular beam epitaxy, casting of single-crystal turbine blades, or steel sheet made by continuous strip casting and cold rolling (advanced processing methods may add value to the material by improving performance or reducing cost);
- *unprecedented properties or combinations of properties due to two or more components* (examples include high-temperature stability and strength in ceramic composites for aircraft engine exhaust components);
- *improvements in properties or process* that allow commercialization of a next-generation product or component, sometimes at lower cost.

Some advanced materials represent *evolutionary* advances, because they provide incremental improvements in performance and utilize existing materials and processes. Others are *revolutionary*—that is, they require substantial additions to the knowledge base. Evolutionary materials are usually producible with existing plant and equipment, whereas revolutionary materials most often require major new facilities. Revolutionary advances generally involve greater risk and cost, and usually represent discontinuous change—that is, to fully exploit their properties often requires developing entirely new compositions or processes. Evolutionary advances are pursued on a more or less continuous basis and, as a rule, are easier to achieve.

All advancements in materials enable new products and systems to be produced that are unachievable with existing materials. In many cases, current-generation materials will be supplemented with advanced materials in next-generation products and systems, because they offer improved performance and, often, lower cost over the service lifetime of the component or system. Other situations require product redesign to capture the full benefits of the advanced material.

Both evolutionary and revolutionary advances are very important in the materials sector. Because commercialization of the revolutionary class of advanced materials usually requires major new facilities and involves the achievement of discrete advances in knowledge, compositions, and processes, the suggestions in this report may be more germane to this class of advanced materials.

At present, the five most critical classes of advanced materials are metals, ceramics, polymers, semiconductors, and composites. Many of the materials in each class are used as structural materials for load-bearing functions; others (often referred to collectively as functional materials) are grouped according to their application for functional purposes. Table 2-1 lists the types of materials in each class.

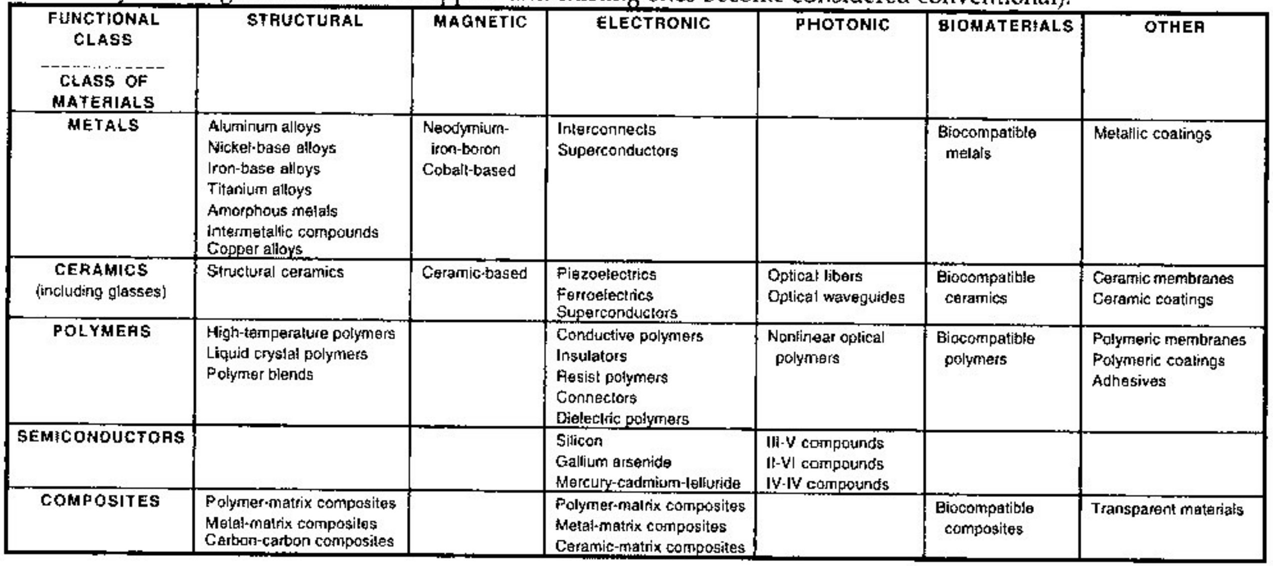
DEFINITION OF COMMERCIALIZATION

"Materials commercialization" as used in this report is defined as: "the cost-effective production and application of advanced materials to meet global market needs." The objective of this activity is to introduce into commercial use materials that are, or ultimately will be, producible, of high-quality, reliable, durable, and economically rewarding to producers and users.

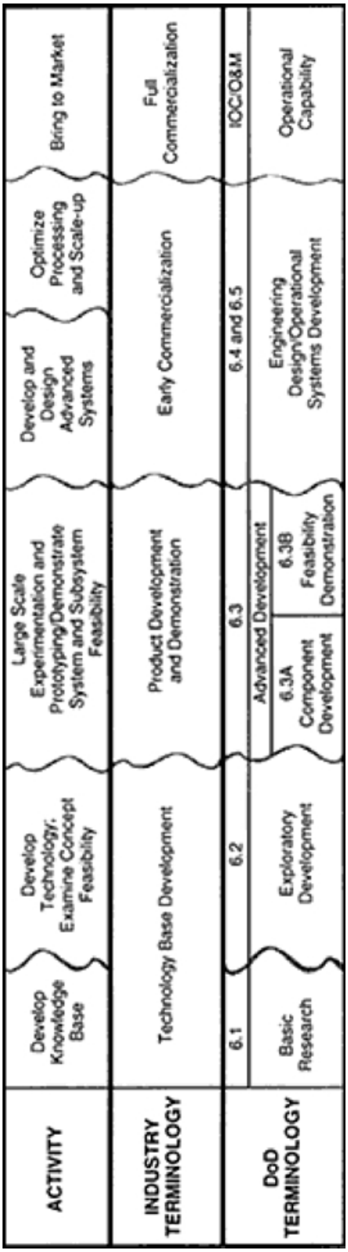
NATURE OF THE COMMERCIALIZATION PROCESS

The process of fundamental and applied research, technology development, and the use of that technology in designing and manufacturing products can be described in a general way. Workshop participants examined the phases of the commercialization process in terms of function or activity that is performed at each step. They compared these activities with regard to the terminology for commercialization used by industry and the DOD and found that the phases in the commercialization process shown in Figure 2-1 were roughly the same regardless of whether government or industrial

TABLE 2-1 Classes of Advanced Materials (It should be noted that the universe of advanced materials is constantly evolving as new materials appear and existing ones become considered conventional).



FUNCTIONAL CLASS CLASS OF MATERIALS	STRUCTURAL	MAGNETIC	ELECTRONIC	PHOTONIC	BIOMATERIALS	OTHER
METALS	Aluminum alloys Nickel-base alloys Iron-base alloys Titanium alloys Amorphous metals Intermetallic compounds Copper alloys	Neodymium-iron-boron Cobalt-based	Interconnects Superconductors		Biocompatible metals	Metallic coatings
CERAMICS (including glasses)	Structural ceramics	Ceramic-based	Piezoelectrics Ferroelectrics Superconductors	Optical fibers Optical waveguides	Biocompatible ceramics	Ceramic membranes Ceramic coatings
POLYMERS	High-temperature polymers Liquid crystal polymers Polymer blends		Conductive polymers Insulators Resist polymers Connectors Dielectric polymers	Nonlinear optical polymers	Biocompatible polymers	Polymeric membranes Polymeric coatings Adhesives
SEMICONDUCTORS			Silicon Gallium arsenide Mercury-cadmium-telluride	III-V compounds II-VI compounds IV-IV compounds		
COMPOSITES	Polymer-matrix composites Metal-matrix composites Carbon-carbon composites		Polymer-matrix composites Metal-matrix composites Ceramic-matrix composites		Biocompatible composites	Transparent materials



ACTIVITY	Develop Knowledge Base	Develop Technology; Examine Concept Feasibility	Large Scale Experimentation and Prototyping/Demonstrate System and Subsystem Feasibility	Develop and Design Advanced Systems	Optimize Processing and Scale-up	Bring to Market
INDUSTRY TERMINOLOGY	Technology Base Development		Product Development and Demonstration	Early Commercialization		Full Commercialization
DoD TERMINOLOGY	6.1	6.2	6.3	6.4 and 6.5		IOC/O&M
	Basic Research	Exploratory Development	Advanced Development 6.3A Component Development 6.3B Feasibility Demonstration	Engineering Design/Operational Systems Development		Operational Capability

Figure 2-1
Phases in commercialization process.

terminology was used. Moreover, each phase, rather than being distinct, often overlaps with the next phase.

The process of developing and commercializing materials is a lengthy one, often requiring 10 years or even longer. A primary reason is that progressing through each phase of the development process requires increasing amounts of material to be processed and fabricated, followed by extensive testing to demonstrate that the properties that make the material desirable have not changed. Before full-scale application, it must be shown that the performance of the material is indeed reproducible, meets all of the necessary standards, and has the necessary life-cycle properties and integrity for the intended application. This process takes time and large capital investments, which is why automotive or airplane manufacturers, for instance, are reluctant to change from a known to a newly developed advanced material. Economics is a large driver in the process as development proceeds from laboratory to commercial quantities. In the final analysis, the materials supplier, component manufacturer, and final product manufacturer or assembler all must make returns on their investments, so materials commercialization ultimately must stand the test of profitability of the final manufactured product.

Workshop participants examined and discussed case studies of four materials—Kevlar, metal-matrix composites, carbon-fiber composites, and carbon-carbon composites—presented at the workshop. They determined that the case studies provided a number of lessons regarding factors that affect the nature and length of the commercialization process—especially for materials commercialization. These lessons follow:

Early Market Assessment. Accurate, early, and realistic market assessment —of application areas as well as estimated sales volume—is important for providing the incentive to make continuing investments in research and development (R&D). Estimating market size and determining the "return threshold" are critical determinants of commercial success.

Risk Versus Payoff. Risk and cost must be balanced by the prospective payoff. If a company does not view the potential profits of the commercialization activity as being sufficiently attractive (weighed against other business opportunities) to warrant the required investment, there will be no motivation to proceed. The developer's business culture and experience must be suited to the demands and risks of commercialization.

R&D Costs Versus Total Costs. It is generally assumed, even by research managers, that R&D represents a very large portion of the total cost of commercializing a new material. However, the bulk of the cost of technological innovation is in pilot-scale manufacture and product introduction. In most instances of commercialization, R&D accounts for a relatively small share of the overall cost of product development. This is illustrated in Figure 2-2, which shows the relatively modest costs for R&D compared with those for pilot development and production. This generic chart is based on the experience of the workshop participants. Thus, processing cost and the ability to scale up efficiently are crucial determinants of the ability to commercialize a new material.

The Need for "Champions." In-house "champions" willing to argue enthusiastically for the commercialization effort for a particular material are essential, and ideally they should exist at both the technical and executive levels. However, overenthusiastic promotion can mislead by generating unwarranted optimism about the technical problems and the prospective market. This excess enthusiasm can be guarded against by frequent verification of technical progress and market projections.

End Users Often Are Not the Customer. There is a kind of "food chain" with respect to materials suppliers and users. The user of a material should provide feedback on performance to the supplier. End users should ultimately drive requirements, but the end user of a material is often not the material supplier's customer; the customer is the parts manufacturer. In such cases, direct supplier-user interaction does not occur, and the supplier may not receive necessary feedback on operational experience with the material.

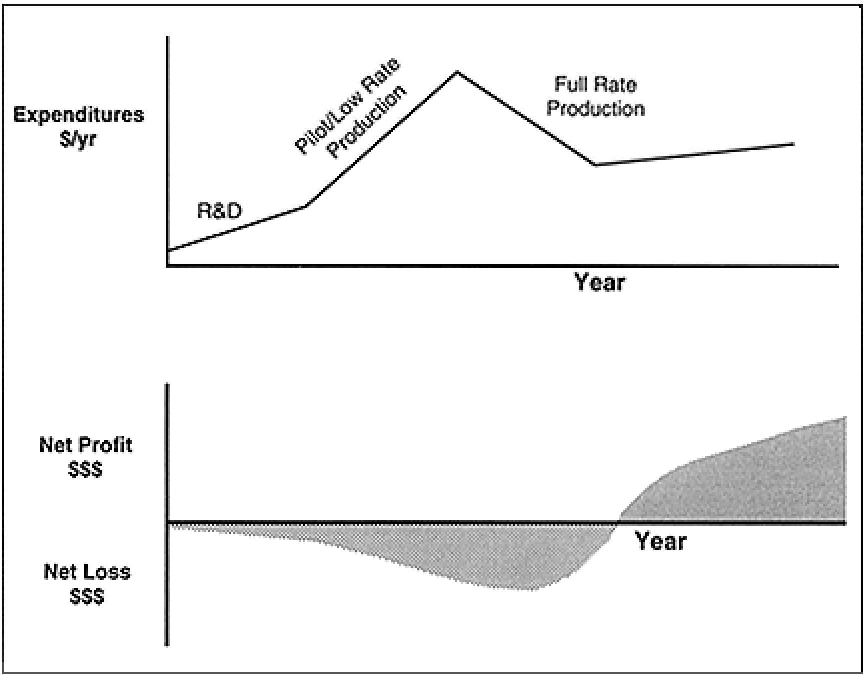


Figure 2-2
Expenditures and cumulative profit and loss in a typical commercialization process.

User-Supplier Interaction. Feedback from the prospective end user to the material supplier is necessary for improving the material. Prospective users should be given small amounts of the material to evaluate. The most fruitful situation is a continuing partnership between the supplier and the user, involving two-way communication of requirements, capabilities, and experience with the material. User-supplier communication between those engaged in a particular commercialization effort is most effective on a specific, in-depth, technical level.

Business Integration Decisions. The economic benefits of integrating downstream (into semifabricated or finished parts/components) and upstream (into raw materials, in the case of composites) can be considerable. Integration permits companies to control the quality, price, and availability of raw materials and allows them to participate in the more profitable end of the commercialization cycle (manufacturing). It also provides them with direct access to the design and fabrication process. Decisions about whether to consolidate operations or integrate the business operations (both vertically and horizontally) are critical, however. The wrong decision can easily be fatal; yet these decisions are difficult to make with confidence in an arena of rapidly changing technology and shifting or small markets.

The Need to Diversify Applications. Major single markets for a material are rare today. More common are multiple smaller markets. While developing a new material to serve more than one customer or application demands more time and money, it actually broadens a company's experience base, allows it to spread costs, and protects it from unforeseen market/technology shifts.

Value of the Entrepreneurial Environment. It is clear that the conventional entrepreneurial environment—characterized by a small, highly motivated team; clear corporate ownership of the technology; and a strong commitment of resources to the specific development effort at the right time—is a superior environment for producing innovations and seeing them to market. However, entrepreneurs often do not have the funding available to sustain an extended R&D and product development effort, particularly if an early market collapses or an adverse decision about adopting the new material is made.

A part of the difficulty the United States has had in competing over the past decade or longer has been the apparent, but not well documented, fact that other nations (notably Japan) have been able to shorten the commercialization process. An examination of several reports dealing with Japanese industry shows a number of lessons that can be learned; however, these apply to the manufacture of such end products as automobiles and electronics rather than the commercialization of materials per se (NMAB, 1986; Clark et al., 1987; Reich, 1989). Nevertheless, these lessons are important, since a material must be incorporated into a product to be useful. These lessons suggest the need for:

- a clear, strong product concept developed early on and maintained consistently by the project team;
- a high degree of cross-functional coordination within the company and with suppliers, including a free flow of information and plans;
- functional integration embodied in a cross-functional project team;
- a strong project manager who has overall responsibility for the timeliness and quality of the product and the authority to pursue it aggressively;
- an emphasis on continuous improvement of products, rather than abrupt discontinuity between successive products;
- a willingness to use off-the-shelf components wherever possible, rather than designing every component from scratch;
- a consumer public eager to purchase and try technological innovations and supported by rigid distribution and dealer networks that demand rapid matching by competitors' products;
- a large and highly skilled engineering work force with a strong product orientation and low turnover rate among companies.

Some of the above lessons undoubtedly are culturally embedded and difficult to emulate in the United States. However, U.S. industry is studying and adopting those features that are compatible with American business culture.

GOVERNMENT STAKE IN THE COMMERCIALIZATION PROCESS

Historically in the United States, most advanced materials have originated primarily in the defense and aerospace sectors. Certainly those were the sectors in which government had a large stake, with national security R&D funded by DOD and space R&D funded by the National Aeronautics and Space Administration (NASA) and DOD. Advanced military and space systems often relied on new materials, and DOD, for instance, was the customer for buying materials first developed under its basic and exploratory research program. This meant that DOD also funded the far more expensive stages of development referred to in Figure 2-1 as "Component Development," "Feasibility Demonstration," and "Engineering Development." The importance of this fact cannot be overemphasized, since the government thereby assumed the risk and expense of moving the material to the commercial stage, which might never have been done otherwise because of the heavy investment required. The initial development of composites for use in military aviation is a good example of this pattern (Chou et al., 1986).

Faster commercialization of new materials is of importance to the government for two reasons: (1) to ensure the government's ability to specify and procure advanced military and space systems that depend on new materials, while obtaining maximum benefits from available materials technologies at costs that represent commercial production, and (2) to enhance the competitiveness of U.S. industries while extending the nation's technological leadership. This dovetailing of military/government and global industrial competitiveness drivers is illustrated in Figure 2-3, and the technologies in question (i.e., those technologies useful to the military as well as the commercial sector) are usually referred to as "dual-use."

Ideally, government agencies should be able to draw upon commercial materials R&D and products, just as civilian industries should be able to draw upon technology developed in government laboratories. The same holds true in all areas of technology, as is detailed in a report of the Center for Strategic and International Studies (CSIS, 1991). Reducing acquisition costs and ensuring the availability of desirable new materials requires developing a commercial market for the material and then meeting that demand with domestic production.

The increasing concern with U.S. competitiveness in the past few years, together with the recent cessation of the Cold War, has led to a different view of the government's role in materials development and commercialization. This view is formally expressed in *Advanced Materials and Processing: The Fiscal Year 1993 Program*, a document that supplemented the President's budget submission for fiscal year 1993 (FCCSET, 1992). The goal of the program is to ". . . . improve the manufacture and performance of materials to enhance the U.S. quality of life, national security, and industrial productivity and economic growth." Four strategic objectives are defined as follows:

1. Establish and maintain the U.S. scientific and technological leadership position in advanced materials and processing.
2. Bridge the gap between innovation and application of advanced materials technologies.
3. Support agencies' mission objectives to meet national needs with improvements in advanced materials and processing.
4. Encourage university and private sector R&D activities in materials technologies, their applications, and their implementation.

These objectives and the accompanying program were one of several presidential initiatives for the fiscal year 1993 federal budget.

For the first time, the government's materials program, funded at $1.658 billion in fiscal year 1992, has, in part, been defined as supporting productivity and economic growth. While the mechanisms for implementation are not well explored as yet, this initiative represents a profound change from previous justifications for the materials program.

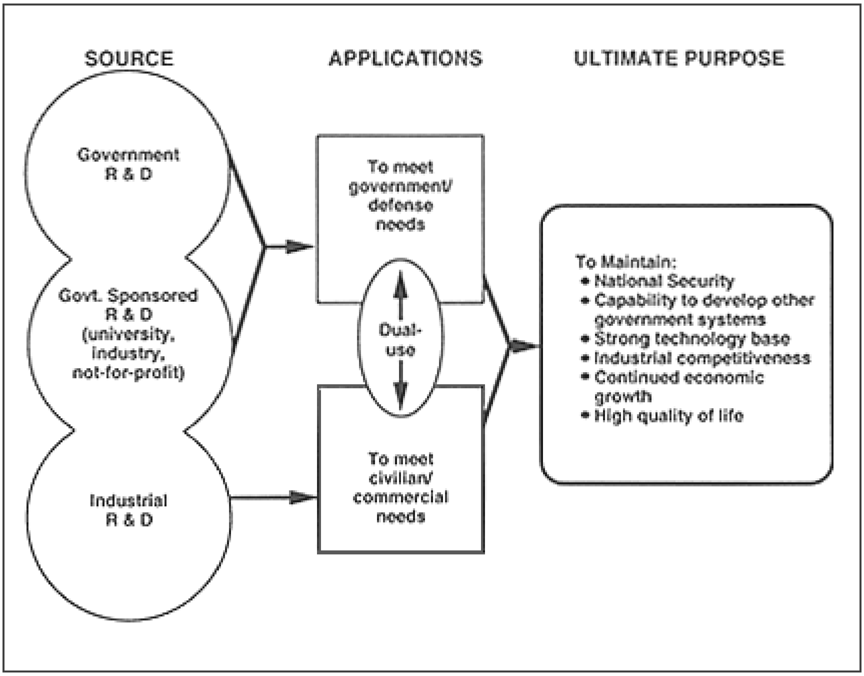


Figure 2-3
Drivers for dual-use technology.

The economics of the defense and aerospace markets have been characterized by high cost, high performance, high risk, and relatively low volume. Commercial applications, by comparison, generally are driven by low cost, resulting in speed, consistent quality, and large volumes. While the defense market is declining, the opportunities in some commercial sectors such as transportation, communication, and infrastructure will be growing over the next few years. Advanced materials applications will be characterized by greater price sensitivity and speed to market. Whereas at one time the defense sector was looked upon as the leader in technological development, it is increasingly becoming a follower, as more complex technologies are developed in a growing commercial sector. The concept of dual-use technologies has become accepted in today's R&D climate to the point where DOD is being urged to replace military with dual military-industrial standards that will be guided primarily by industrial needs (FCCSET, 1992).

3—

Factors Affecting Materials Commercialization

It is generally recognized that one of the key problems in the commercialization of new materials is the difficulty of moving from R&D to the point of commercial production. This transition centers around that part of Figure 2–1 marked "Component Development and Feasibility Demonstration" (DOD Terminology) or "Product Development and Demonstration" (Industry Terminology). It is here that feasibility for commercialization and confidence have to be established before proceeding. Findings on this point are explicit and come from varied sources. For example, the Defense Science Board said in 1987 that:

> . . . both the Defense Department and commercial industry are seriously deficient in rapidly moving technology from R&D to systems and products. . . . The greatest opportunity to improve the rate and effectiveness of this transition process is by increasing focus on the early advanced development phase of the S&T [science and technology] program, that is, Budget Category 6.3A.
>
> (DSB, 1987)

Similarly, the Carnegie Commission addressed the problem of "Stimulating the Diffusion of High-Leverage Technologies from the Laboratory to the Field:"

> The armed services, like industrial companies, have difficulty transferring their best technologies from the laboratory to new products in a timely way. The DOD's 6.3A program is intended to facilitate such transfer by funding the building and testing of "breadboard" prototypes that, while inexpensive and quickly assembled, still allow for demonstrating the feasibility of a technology in the military application foreseen for it.
>
> (CCSTG, 1990)

As part of the DOD-wide response to such concerns, the U.S. Air Force Materiel Command has initiated a Materials Transition Program that focuses on what it terms the "transition gap" between the latter stages of 6.2 (Exploratory Materials Development) and the early stage of 6.3 (6.3A, Component Development). Figure 3–1 describes the objectives of this program.

There are similar initiatives on the industry side. For example, the U.S. Advanced Ceramics Association launched a "Bridging the Gap Initiative" in late 1990 aimed at shortening the time between R&D and commercialization of advanced ceramic technology. The association identified the "bridge problem" in a somewhat broader area than the DOD (Figure 3-2), but the formulation of the problem and the objective of the initiative are the same (USACA, 1991).

A multitude of barriers need to be overcome to lead to successful commercialization of a material. In general, these barriers can be categorized as *technical*, such as the availability of test procedures and property data, processing and manufacturing technologies, and sensitivity to flaws in materials and processes; *regulatory/legal*, such as government procurement policies, intellectual property rights, environmental protection, and health and safety; and *economic*, such as R&D costs, market size, interest rates, cost of capital facilities, and profit goals. These barriers are described in greater detail in the balance of this chapter—with emphasis on the technical factors, since these represent the expertise of the workshop participants and the National Materials Advisory Board (NMAB).

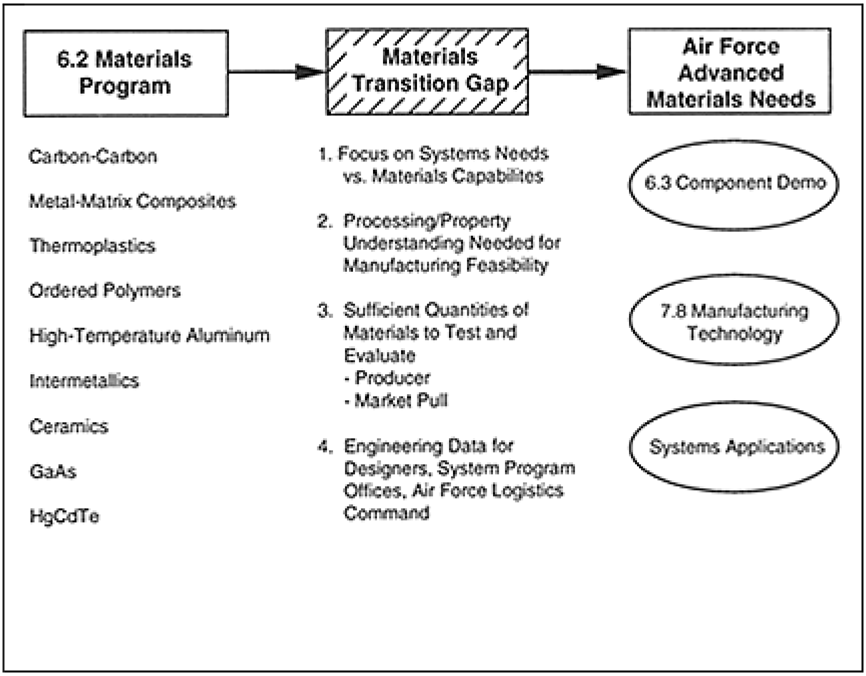


Figure 3–1
U.S. Air Force Materials Transition Program (Source: R. L. Rapson, Materials Laboratories, Wright Laboratories, Wright-Patterson Air Force Base).

TECHNICAL FACTORS

Definition of Technical Goals

The developer of a new material often fails to clearly establish the goals that a new material should meet. Since materials development driven by theory and computer simulation is still in its infancy, most materials development is conducted empirically. Goals are often chosen on the basis of experimental observation rather than application needs. Developers sometimes fail to distinguish between the search for revolutionary developments to achieve major breakthroughs in properties, and evolutionary development to achieve incremental improvements in existing materials and performance levels. In his article, "Turning Ideas into Products," Gomory describes these different approaches for the electronics industry by defining "cyclic development" as contrasted with "ladder advances" (Gomory, 1988). He defines the "ladder" process as a step-by-step reduction to practice of a new idea. In his terminology, the invention of the

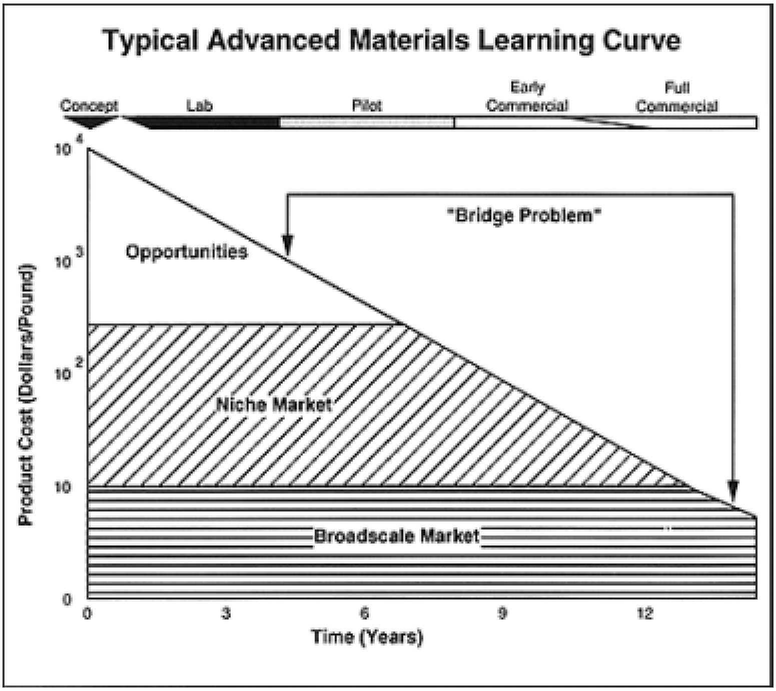


Figure 3–2
U.S. Advanced Ceramics Association "Bridging the Gap" Initiative (Source: USACA, 1991).

transistor is an example of the "ladder" process. "Cyclic development," by comparison, is a more common process of repeated incremental improvement. In this type of improvement process, an existing product gets better and develops new features year after year. The cumulative result of these incremental changes can indeed be profound. A good example, as he points out, is that 20 years of incremental improvement has resulted in advancing from one bit on a chip to one million bits.

Too often, revolutionary development efforts set overambitious goals for materials performance, which in turn creates an all-or-nothing approach, resulting in failure. In general, a balance must be achieved by the developer between high-risk, high-return goals and incremental improvements with well identified objectives.

One of the problems with defense-stimulated or space-stimulated materials developments has been a mission-oriented agency that often sets goals or specifications relating to narrow mission objectives, thereby ignoring potential commercial requirements or existing commercial products. This practice can severely limit the market for a material and drive up production costs. A recent report by the Carnegie Commission addresses this question in detail (CCSTG, 1991), while the use of commercially developed technologies for defense purposes is treated in an Office of Technology Assessment report (OTA, 1989).

Difficulty of Scale-Up

Scaling-up a new material from laboratory quantities to precommercial, and eventually commercial quantities, often results in unforeseen obstacles, thus posing formidable risk to the industrial developer. The cost of scaling-up is especially severe for small entrepreneurial companies whose resources often are too limited to invest in new process and manufacturing equipment. In addition, such equipment may not be able to reproduce the material and its properties quite like the samples produced in the laboratory. Pilot demonstrations are the most important part of materials development in transitioning from invention in the laboratory to commercial applications. Process modeling is a powerful technique to minimize these difficulties, but it requires skills and resources not available to everyone.

The DOD has supported some pilot production programs (as shown in Figure 3-3) through activities like the Industrial Modernization Incentives Program. This program was originated by the Air Force to encourage companies that make up the defense industrial base to modernize their facilities. The goal of these modernization efforts has typically included increased production efficiency, improved product quality and durability, lower product life-cycle costs, and reduced lead times (Schafrik & Fiorino, 1992).

Another DOD program addressing pilot production is Title III of the Defense Production Act, which deals with guaranteed sales and other incentives to meet strategic goals for defense (Defense Production Act, 1950). Title III has provided for guaranteed purchases of specific new materials, thus creating a sufficient market to meet strategic goals for defense and, in some cases, stimulate other applications. Section 302 of Title III also authorized "loans to private business enterprises (including research corporations not organized for profit) for the expansion of capacity, the development of technological processes, or the production of essential materials . . . " High-purity silicon, discontinuous reinforced aluminum composites, and synthetic rubber are all examples of materials whose development was stimulated by Title III—which expired in October 1990. Fortunately, Title III was reauthorized by Congress in November 1992 and, in fact, has been amended to include several new features related to commercialization. Among these is language that allows Title III support to expand capacity to meet defense and nondefense combined needs and a statement to the effect that an important purpose of Title III is the creation of an economically viable production capacity.

A third program is the Manufacturing Technology program, established by DOD and designed to translate materials into

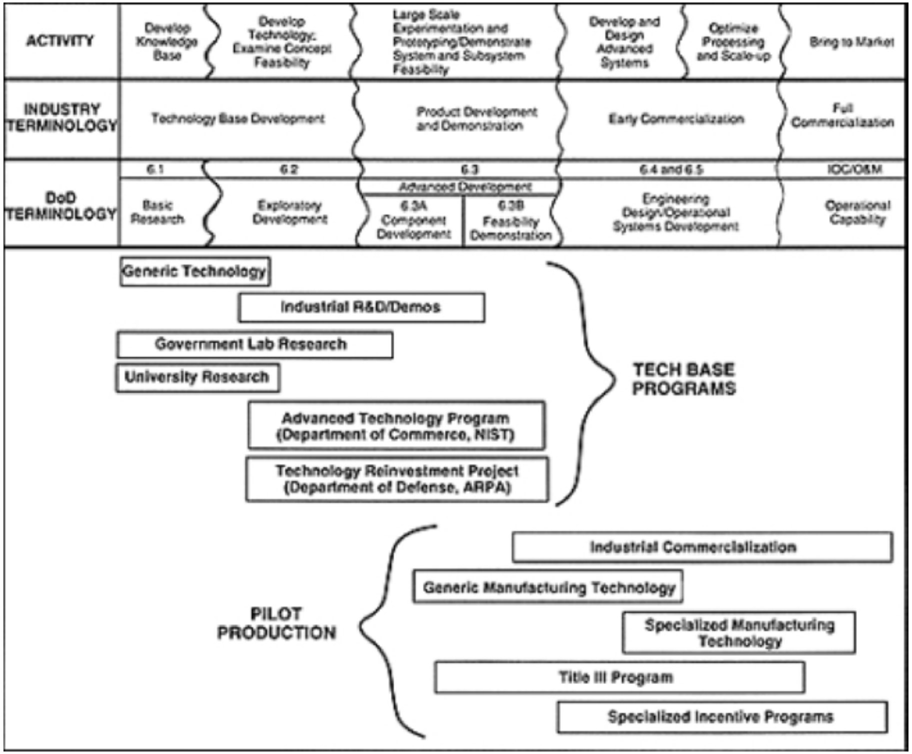


Figure 3-3
Commercialization-related programs supported by the federal government and by industry.

components and systems. Despite their usefulness, however, the Manufacturing Technology program has undergone funding reductions in the last couple of years, and the Industrial Modernization Incentives Program has been eliminated by DOD.

A program established by Congress in the Technology Competitiveness Act of 1988 provides technology development grants to single businesses, independent research institutions, or joint ventures (NIST, 1991). Awards are made for generic technology development and precompetitive technology, the latter being defined as "R&D activities up to the stage where technical uncertainties are sufficiently reduced to permit assessment of commercial potential and prior to development of application-specific commercial prototypes." One of the awards relating to materials development in 1992, for instance, was to the Nanophase Technologies Corporation to "develop the technology to produce commercial quantities of new nanocrystalline ceramics" (New Technology Week, 1992).

Design, Processing, and Data Bases

Detailed design methodologies based on conventional materials are often not valid for new materials. For example, polymeric and composite parts are designed to net shape, while metal parts often are designed to be machined. There are major differences in deformation behavior; metals yield and strain-harden, while composites are stiffer, and ceramics do not yield. There are also significant differences in joinability—metals can usually be welded and mechanically fastened easily, while non-metallic materials cannot. Finally, there are differences in the directionality of properties—metals can usually be processed to have isotropic properties, while composites are anisotropic. These differences, and others, require fundamental changes in design approaches.

To achieve the low-cost materials and processing necessary to satisfy commercial markets requires widespread application of concurrent engineering. This will permit real-time exchange of information regarding design needs and materials capability. Concurrent engineering, which makes the interfaces between design and manufacturing more transparent, has the potential to reduce the time required to design and produce a product that incorporates new materials.

Materials-design data bases are usually very costly and take a long time to develop. There are too few data bases available, and they are not standardized. Yet reliable data bases are essential to the identification of realistic application opportunities. To make matters worse, materials test requirements and the associated standards are often inadequate or lacking.

Knowledge of how most materials perform over their life cycle in a given component application is incomplete. In the case of composites, for example, deformation and failure mechanisms are difficult to define and measure, making life prediction problematic. Accelerated tests to predict expected long-term performance are difficult to develop. This lack of life-cycle data inevitably leads to conservative design, using larger margins of safety than would otherwise be necessary. It also makes it difficult to fairly compare materials on the basis of lowest life-cycle cost, since initial acquisition cost and life-cycle cost are usually very different.

Standards and International Standardization

A number of private sector standards-writing organizations exist in the United States to develop domestic standards; they include the American National Standards Institute; the American Society for Testing and Materials; and several activities under specific technical societies, such as the Institute of Electrical and Electronics Engineers and the Society of Automotive Engineers. The American National Standards Institute is not only the coordinator of standards writing but also the member body in the International Organization for Standardization. U.S. industry appears to be reluctant to pay for and participate in international standard-setting activities, while by contrast, Japanese and European participants are fully subsidized by their respective industries—to the extent that Europeans and Japanese are beginning to dominate the chairmanship and membership of the International Organization for Standardization and other technical standards committees. The result is that other countries' market and product requirements are gaining prominence in the standards, while U.S. manufacturers are increasingly becoming followers in the standards development process.

The National Institute of Standards and Technology held a workshop in April 1990 to examine the role of the government in standards-related activities. A major topic of discussion was whether there is a need for a coordinating function to facilitate the timely development of standards by existing standards organizations. (A potential model for such a coordinating role is the Standards Council in Canada, in which the government plays the coordinating role.) No strong consensus was reached. However, in a summary report the institute set forth a number of conclusions dealing with standardization and conformity assessment (Leight, 1990). Several of the conclusions related to the need for closer interactions between government and industry and the need for more effort by industry to support, participate in, and monitor standard-setting activities. The report called specifically for the government to "intensify negotiating efforts to ensure foreign acceptance of products based on testing and certification performed within the United States," and to:

> . . . sponsor or co-sponsor with interested parties from the private sector a series of workshops with various industry sectors to specify more precisely the needs for coordination and representation of U.S. conformity assessment interests abroad. Then, appropriate systems should be developed to meet those needs and to promote effective application of these mechanisms in behalf of U.S. manufacturers and exporters. Particular consideration should be focused on the division of

> responsibilities between Government and the private sector in a cooperative mode of operation.

The danger in not maintaining leadership and full participation in international standards development is that U.S. industry will eventually be forced to accept the standards promulgated by other international or quasi-international groups such as the Community of European Nations. U.S. industry must be able to market its products within the world market without restrictive standardization barriers. Greater support and coordinated action by U.S. industry are essential to industry's competitive future.

Inflexibility in Manufacturing

The resistance to change on the part of design engineers, materials manufacturers, and system developers is considerable—and understandable. This resistance is partly due to the fixed design concepts for systems and the high cost of requalifying materials when specifications are changed.

Inflexibility in manufacturing is an impediment to the introduction of new materials. The lack of involvement of materials experts in designing products and manufacturing operations often means that the selection of materials is frozen very early in the product development cycle. As a consequence, new materials and processes cannot be used to enhance products and improve manufacturing or to solve manufacturing problems. Once the product is manufactured, the process is frozen. Insertion programs to replace specific components with an improved material after a thorough design analysis are one way to break this impasse and allow improvements through incremental application of new materials technology. An example of such a program is the ceramic insertion program initiated by the Advanced Research Projects Agency in early 1991.

For companies to take advantage of newly developed materials, their products and their associated manufacturing systems should be considered concurrently and with as much versatility as the particular application allows. System developers should be made aware of new materials that would provide superior performance. They should incorporate into their design and manufacturing scheme the potential to quickly insert improved materials technology at any point in the lifetime of the product family, not just during the initial design. This will allow the fairly rapid accumulation of realistic service experience. If low-risk opportunities are selected, the cost of these demonstrations can be minimized. It must be recognized, however, that the narrow focus of insertion programs, while important for building confidence, will limit the full performance potential of the material.

Another mechanism necessary to improve the manufacturing process is a closer working relationship between materials suppliers, parts fabricators, and end users. In commercializing the use of a new material, process, or product, industry is increasingly turning to consortia that offer the opportunity for shared technical development, shared risk and cost, and enhanced communications. The Automotive Composites Consortium is a good example in the structural materials area, while the Semiconductor Manufacturing Technology Corporation is a good example in the electronic materials and components area. Such consortia may or may not include government funding. Likewise, federal laboratories may be involved in such consortia if their expertise is applicable to the overall good.

Engineering Education

During the 1970s and 1980s, engineering schools concentrated on teaching engineering science rather than engineering design (MSB, 1991). As a result, there is currently a shortage of the talent needed to take advantage of advanced materials through cost-effective design and new-product application.

Industries such as the automobile manufacturers are designing to engineering requirements derived from customer requirements that are established from market surveys and clinics. New concepts such as "design for manufacturability" and "design for assembly" are being used. In addition, the concept of recyclability of materials and components is becoming important. All of these approaches must be taught to materials engineers who will interface with, or in some cases practice, the engineering design of products.

It is essential that U.S. industry have an adequate supply of engineers who understand materials processing and manufacturing. Because government funding of university research primarily emphasizes basic research, students tend to be educated in those areas in which the research faculty are proficient—fundamental theory, analysis, and discovery—rather than in making things and making them work economically. The emphasis in university engineering education on materials design, materials processing, and manufacturing needs to be increased (NRC, 1989).

A valuable adjunct to academic programs would be some form of "practice school." In this model, the student works on actual professional assignments in the field, with real responsibility, for several months at a time. This model could be adopted by materials and engineering departments for educating students in materials processing and manufacturing. The National Science Foundation's Engineering Research Centers and Science and Technology Centers Program are a step toward this concept. Germany's Fraunhofer Institutes, with their employment of doctoral students in research and their apprentice programs for masters and undergraduate students, are an even stronger embodiment of this approach.

The best known example in the United States is the Chemical Engineering Practice School at the Massachusetts Institute of Technology, first established in 1916. Students spend up to eight weeks at each of two plants working in teams on specific problems. They design the problem-solving approach, gather the necessary data, and make oral as well as written reports with recommendations (Gushee & Margolin, 1992).

The success of these concepts critically depends on a commitment by industry to make positions for individuals trained in processing and manufacturing more attractive. Such a strategy would be in industry's best interest, since better trained employees will contribute to a company's competitiveness.

Equally important are continuing education programs for engineering designers and manufacturing engineers already in practice, so that conventional paradigms of design and manufacture, based on metals, can be resynthesized to take advantage of advanced materials. Technical personnel without degrees who are involved in engineering and manufacturing also should have access to additional training, especially with respect to new materials.

REGULATORY/LEGAL FACTORS

Intellectual Properties

Two primary issues that relate to intellectual property rights were identified by workshop participants: patent rights under government contracts and process-intensive patents.

Rights Under Government Contracts

There is both a perceived and a real issue concerning the use of patented technology in the performance of government contracts. The basis for both concerns is the Authorization and Consent clause that is included in most contracts with the U.S. government, at least those in which production of hardware is concerned.

Under one form of this clause, the infringement of third party patents is allowed because the government assumes the liability for this action. If the owner of the patent pursues an infringement to recover damages, either in the form of lost royalties or any other form, the suit is ultimately maintained against the government. For example, Company A owns the Composition of Matter patent for a material, but Company B needs to use the material to make hardware for the U.S. government in fulfillment of a contract that includes the proper form of the Authorization and Consent clause. Company B can use the patented alloy for this purpose. If Company A then brings suit against Company B, Company A has the Authorization and Consent clause as a defense, and the suit is ultimately maintained against the government for damages. Moreover, Company A cannot prevent Company B from using the patented material, so exclusive access to the material by Company A is breached. Thus, there is a real loss to Company A, because the right to exclusively practice its patented technology is abridged, and, for most companies, there is a perceived difficulty in bringing suit against the government with its vast resources. The loss presumably is compensated by the recovery of damages against the government in the U.S. Court of Claims.

There is a related situation that often is confused with the Authorization and Consent clause. That is the case of patented technology that is owned by a company but was developed in whole or in part by the company as part of a government-funded R&D effort. In such cases, the government retains the right to a royalty-free license for use in all government-purchased hardware. This seems reasonable, since part or all of the development expense was borne by the government. The company that owns the patent has the exclusive right to control the practice of the technology in all commercial situations, however.

There is also a concern related to proprietary data (i.e., data that is not patented) rights. The Center for Strategic and International Studies committee, chaired by Senator Jeff Bingaman, addressed this problem and its effects:

> DOD's emphasis on obtaining unlimited rights in technical data, including the right to distribute

> proprietary information to competitors, has created a major barrier to commercial and military integration. Under current regulations, a company could well lose its proprietary rights. This makes firms extremely reluctant to incorporate commercial technologies into a DOD contract. The emphasis on unlimited rights also discourages companies from exploiting the commercial opportunities of defense-supported technologies. Experience has shown that technologies that are potentially available to all companies will be exploited by none.
>
> (CSIS, 1991)

Better protection of proprietary property rights of government contractors would encourage expansion of the pool of qualified vendors. The Center for Strategic and International Studies committee recommended that "All technology developed under contract, even if developed with public funds, should be the property of the contractor, subject to limited Government Purchase License Rights."

Process Intensive Patents

International differences in the patent process and patent enforcement often inhibit commercialization by U.S. industry of new materials that tend to be more process intensive. Process patents are especially difficult to enforce, because it is difficult to demonstrate infringement. This is especially important in engineered materials, where materials performance is integrally tied to processing technology. The use of neutral third parties to confirm or deny the occurrence of process patent infringement could be helpful in resolving process patent disputes quickly and possibly in deterring infringement.

Antitrust Concerns

Antitrust concerns are improving for precompetitive cooperation among companies but are still formidable for production activities. Joint ventures ease this difficulty but are an expensive legal solution to the fundamental need for easier cooperation. The United States is still at a competitive disadvantage in this area with respect to other industrialized countries. If antitrust restraints on cooperation in production were to be relaxed, pilot plant facilities, for instance, needed for scaling new materials from the research to the production stage, could be used by more than one company. A relaxation of antitrust laws with regard to pilot operations would not only help to overcome technical difficulties but would also reduce the risk (both actual and perceived) that industry faces in the materials commercialization process.

Export Restrictions

Export controls, imposed by the Department of State or the Department of Commerce in the interest of national security, in many cases restrict the ability of U.S. materials producers to expand their markets. A byproduct of restricted access is closed technical meetings, which reduce the flow of knowledge among American companies, restrict the peer review process, and inhibit open publication. These controls appear to be easing somewhat at present. However, the State, Commerce, and Defense departments need a better method for determining precisely how far to go in balancing commercial interests against national security considerations in their application of the International Trade and Arms Regulation and export control legislation. A recommendation made by a National Research Council panel is that the United States and other members of the Coordinating Committee for Multilateral Export Controls change the basis of their technology transfer restrictions from a policy of general denial of dual-use (military and commercial) controlled items to a policy of presumed approval to export, based on verified end-use of the product (COSEPUP, 1991). This issue is currently being addressed by the coordinating committee, especially with regard to trading with the former Soviet Union, and early indications are that export control regulations may become liberalized.

Environmental, Safety, and Health Regulations

Regulations concerning environmental impact of materials processing and manufacturing add to the cost and risks of commercializing new materials. In the U.S. steel industry, for example, the commonly quoted assertion is that environmental compliance costs represent $10–$20/ton, or 2.5–5.0 percent of the price of steel. The percentage may seem small, but for most U.S. steel companies this cost is equal to or greater than the profit margin in today's market. In the aluminum industry, one major domestic producer estimates that its environmental costs amount to roughly 1 percent of total sales (accounting for various offsets reduces the figure to about 0.75 percent). The added cost is reported to be $0.09–$0.15/1b for copper and $0.06/1b for lead (NMAB, 1990).

Environmental regulations and controls in most developed nations, such as Japan and the European Economic Community, now equal or exceed those in the United States. But in the developing world and the nations now emerging from behind the former Iron Curtain, environmental regulations and controls are much less stringent. Many of these nations, while not competitors now, will be competitors in the future. The relatively low costs they incur in addressing environmental concerns will be a factor in that competition.

As environmental concerns evolve, there often are conflicts between federal, state, and local laws that magnify paperwork and hamper compliance. A recent Office of Science and Technology Policy report states that an integrated approach to energy and environmental issues is necessary in the utilization of emerging technologies.

> It is important that environmental, health, and safety requirements should be well defined and the process for compliance should be streamlined. There must be a common ground that provides for both preservation of the environment and the competitiveness of U.S. industry.
>
> (OSTP, 1990)

ECONOMIC FACTORS

Cost Versus Risks

The high cost of materials R&D, along with the even higher costs of testing, pilot-scale manufacture, and technology demonstration, represent a substantial up-front investment. At the same time, the return on that investment is unknown and will not become known until long after most of those funds have been spent. In today's turbulent business environment, taking such risks is hazardous. This is as true for many other technologies as it is for materials.

Market Size

Where the government is the prospective customer for a new material, actual demand in terms of volume can be quite small. For example, specialty materials being developed for the National Aerospace Plane would initially find application in very few vehicles. From the perspective of industry management, the potential risk is offset by the possible benefits—a larger demand may develop downstream, or new applications may be found for materials developed for this project. However, some materials developed for government purposes may never achieve dual use.

Short-Term Management Goals

Given the substantial commitment of dollars and time required for materials technology development, the often noted short-term profit outlook of corporate management is a barrier to long-term innovation. There are some emerging examples of American companies that have enhanced their competitive posture by deemphasizing traditional short-term financial management measures and focused on product quality, employee involvement, and speed to market. These examples include Nucor (rapid incorporation of innovative, high-risk steelmaking technologies), Ford Motor Company (fundamental engineering and manufacturing changes that resulted in significant quality improvements), Boeing Airplane Company (reducing 777 development time through reliance on "paperless" CAD/CAM tools), and 3M Company (active encouragement of entrepreneurially minded employees to exploit new technologies). Over time, corporate cultural transformation in the United States will make focusing on the correct measurements "second nature." History suggests that such a transformation must start at the top of the organization and work its way down.

High Cost of Capital Facilities

Companies are often constrained to the use of installed or existing capital facilities, because the perception of small markets makes it hard to justify new investment. Yet new materials often require costly new facilities for production and to guarantee reproducibility. At those times when the cost of capital is high in the United States relative to other countries, U.S. companies are less competitive, and funding for commercialization becomes more difficult.

Government Procurement and Funding Policies

Several of the most significant financial impediments to commercialization are those imposed by government procurement practices. Some of the barriers to commercialization of new materials derive from restrictions imposed by government. Some examples are given below.

Least-Cost Procurement

The policy of least-cost procurement has apparent budgetary advantages but can be detrimental to the quality of materials and systems procured. This policy is now beginning to shift toward permitting the use of "best value supplier" rating systems for government subcontracts. These rating systems permit government and contractor procurement personnel, in selecting vendors, to balance considerations of cost with considerations of timely delivery, quality, and technical performance.

Overabundance of Suppliers

The practice of encouraging a large pool of suppliers may be detrimental to materials advancement, because, in an environment of small markets, circumstances often dictate the need for only two or three vendors. A large number of suppliers can mean that the business is profitable for none.

Cost Accounting Rules

The government's cost accounting system fails to take adequate account of the technology development cycle. Its perspective of basing allowable profit as a fixed percentage of material or product cost is foreign to commercial practice. It tends to reward high-cost suppliers who do not invest in improving their technology. It inhibits

its innovative suppliers by restricting gains from employing risk capital that could be used to advance the materials and process technology. For prime contractors, the Independent Research and Development cost recovery system provides some help in countering this problem.

First Cost Versus Life-Cycle Cost

The practice of selecting materials according only to initial cost ignores the importance of life-cycle cost, which is often substantially lower for advanced materials than for the conventional materials they replace (NMAB, 1991). Acquisition and finance managers should understand and promote the importance of life-cycle cost thinking, including environmental and recycling costs.

Funding Uncertainties

Funding uncertainties engendered by the annual budget cycle and lack of follow-through on approved programs create a lack of confidence in the ability of government to maintain progress toward planned programs and goals. This can act as a disincentive to commercialization of a new material if the market for that material is largely tied to a prospective government-funded system that can be radically changed or cancelled with very short notice.

4—

Strategies for Overcoming Commercialization Barriers

Discussion of the various issues detailed in the previous chapters led to a series of findings on the barriers to commercialization. Strategies on how to overcome such barriers are suggested following each of the findings. These strategies fall into three main categories: (1) those that relate to the government's role and actions it can take to facilitate the commercialization process; (2) those that pertain to industry in its pursuit of competitive new materials; and (3) those that relate to the role of educational institutions in producing a new generation of materials scientists, engineers, and technicians.

It should be pointed out that most of the strategies require a degree of cooperation among all three sectors, so grouping them under any one sector implies a lead responsibility only. Two particular strategies for which a lead responsibility is difficult to assign are designated as being for all three sectors.

FEDERAL GOVERNMENT

Finding: The most difficult and critical step in the commercialization of a material is scaling-up from laboratory quantities to precommercial and eventually commercial quantities. The federal government has supported such development on occasion, especially through programs initiated by DOD including the Title III of the Defense Production Act and Manufacturing Technology programs. Other programs, such as the Advanced Research Projects Agency's Technology Insertion Programs and DOD's Manufacturing Technology Program, helped to create a demand for advanced materials and processes by reducing the front-end risk to industry. In view of the new mission expressed in the fiscal year 1993 presidential initiative on advanced materials and processing, which includes among its strategic objectives the bridging of the gap between innovation and application of advanced materials technologies, government should organize itself to support this objective. A necessary condition is the timely, wide dissemination of materials R&D information.

The federal agencies involved most likely would be those having major materials programs as outlined in the Advanced Materials and Processing Program Plan report (FCCSET, 1992). The strategy suggested is that:

- *The federal government could establish a clearinghouse activity to serve as a single source of readily available information containing relevant aspects of all federally funded materials programs that spanned the range of basic research through pilot production. The information would describe the materials being developed and commercialized under federal sponsorship, the funding levels, milestones, and so on. Such a data base would allow better coordination among all federally funded materials efforts, resulting in reinforcing comprehensive efforts: for example, facilitating the identification of program gaps and overlap areas. Industry and academia would have access to the "big picture" and thus be able to anticipate when materials of interest would be available for use, In addition, industry could be asked to assess the commercialization potential of specific development* *efforts, taken as a whole; appropriate changes could then be made early enough to ensure that commercialization would not be delayed due to an oversight.*

Finding: Materials development supported by government agencies has often been confined to narrow mission-related objectives. Future commercial applications of advanced materials will almost always include potential markets beyond initial government applications, however. Ignoring potential commercial requirements can severely limit the market for new materials and increase production costs. The NMAB suggests the following strategy for dealing with this issue:

- *To provide as broad an application window as possible, government materials R&D programs could incorporate along with the known government requirements, or otherwise address, The key material needs for leading commercial applications. Appropriate mechanisms to discover and assess these needs would have to be established as well.*

Finding: The end of the Cold War and government policies designed to promote exports are leading to a reexamination of export control regulations. These regulations can limit the use of advanced materials technology, often without apparent meaningful purpose. The current regulations can also unnecessarily interfere with the interactions between U.S. firms and their foreign partners. This restricts the broadening of the U.S. technical base and limits U.S. firms' access to overseas markets. The NMAB suggests the following:

- *A study by the Committee on Science, Engineering and Public Policy recommended that the basis of technology transfer restrictions be changed from that of a policy of general denial of dual-use* *items to a Policy Of presumed approval for export, based on verified end-use of the product (COSEPUP, 1991). This recommendation could be used as a framework to address the necessary changes to the export control regulations.*

Finding: A number of barriers to commercialization of new materials were identified that relate to economic and regulatory factors. Such factors affect commercialization of many products and processes and are not confined to materials. Moreover, many of these factors are part of the dynamic debate within all three branches of the federal government, and undergo continual change. For instance, tax incentives, government procurement policies, and intellectual property protection clauses are the subject of numerous legislative actions and judicial decisions within the course of a year. The NMAB suggests the following strategy:

- *Economic and legal barriers to commercialization, as well as financial incentives, could be examined in detail by appropriate experts to determine what changes could prudently be made to assist in accelerating the commercialization process.*

INDUSTRY

Finding: Consortia and other focused mechanisms for precompetitive development can do a great deal to help industrial companies share risks and costs while speeding technical advances through exploration of parallel paths. Such consortia can be useful if organized horizontally (e.g., several companies that are essentially in the same business) or vertically (e.g., several companies that include materials suppliers, manufacturers, and end users). Cooperative efforts can include precompetitive R&D, development of design data and test requirements, development of technical commercial requirements, collection of life-cycle data, and sharing of high capital cost facilities. The NMAB suggests the following strategies to deal with these issues:

- *Focused, cooperative, cost-shared efforts can speed the commercialization of materials through such activities as precompetitive R&D, demonstration of process reproducibility, application development, development of design data bases, and joint-use capital facilities. Industry could establish consortia that include materials suppliers, part fabricators, and end users. As appropriate, the expertise and unique facilities of the federal laboratories can be integrated into such consortia.*

Finding: Material suppliers typically provide their products to makers of semi-finished products, such as forging and casting houses. This tends to decouple material companies from their ultimate customers: the end users. Direct links between the material suppliers and the end users would provide the materials industry with first-hand knowledge of user needs and the users with first-hand appreciation of capabilities within the materials industry. Such a strategy is suggested:

- *An informal interactive forum, implemented on an individual basis or an industry-wide basis, could allow the necessary interchange of information and improve market pull and product focus for material producers. Existing mechanisms already in place at various trade associations can facilitate these interactions. Use of video conferencing electronic communications would further reduce the cost of maintaining the forum.*

Finding: Inflexible product design approaches and manufacturing processes often significantly impede the introduction of new materials. For companies to take advantage of newly developed materials, products and their associated manufacturing systems should be considered concurrently and with as much versatility as the particular application allows. Revolutionary new materials generally can fulfill their complete potential only if new design methods are applied to new products. The consequence is that advanced materials often wait "on the shelf" until new markets develop. However, the insertion of improved materials to incrementally improve existing products can be an attractive way to use an existing market to build demand for an advanced material, even though it may not exploit the material to its fullest capability. System developers should incorporate into their design and manufacturing scheme the potential to quickly insert new materials technology at any point in the lifetime of the product, not just during the initial design. The NMAB suggests the following strategy to deal with this issue:

- *A product improvement strategy for making use of advanced materials should be considered. Such a strategy requires concurrent updating of product design approaches to reflect the unique aspects of the new material. Consideration must also be given to any environmental and use changes that the product might experience as a result of added capability.*

UNIVERSITIES

Finding: There is a need for engineers who are proficient in designing and processing new materials and in designing and manufacturing products that successfully incorporate these materials. Unless design and manufacturing engineers are available who can capitalize on the novel properties of new materials, the promise of these materials will not be realized. To improve the supply of such engineers, the emphasis on materials processing, design, and manufacturing in university engineering education must be increased. A valuable adjunct to new academic programs would be some form of "practice school." In this model, a student works on actual professional assignments in the field, with real responsibility, for several months at a time. The NMAB suggests the following strategy:

- *A university-led partnership could be used to develop realistic ways to encourage and support revised, or entirely new, design approaches and methods that would allow full exploitation of advanced materials properties, avoidance of failure modes, and so on. For example, the "practice school" model could be extended to include materials processing and manufacturing education.*

Finding: Advanced materials technology often eclipses the experience and knowledge of practicing design engineers and manufacturing engineers. University-led continuing education programs for experienced design engineers and manufacturing engineers can bring this community up-to-date with new materials whose properties do not necessarily parallel their experience base with metals. It would usually be far more cost-effective to bring these professionals back to the university environment to gain additional knowledge than to learn by trial-and-error in their normal work environment.

- *Continuing education programs for experienced practitioners could be an effective mechanism for bringing them up-to-date, providing a necessary knowledge base and expert tutelage. As a result, experienced professionals would be able to* *resynthesize their conventional designs in line with useful new paradigms.*

Finding: Non-degreed technical personnel perform many crucial tasks throughout engineering and manufacturing. Their experience base is derived largely from learning successful procedures. Extending their experience is necessary to fully exploit materials that are on the verge of being commercialized. Traditionally, technical societies have filled this need, and they have the capabilities to develop such training courses. The NMAB suggests the following strategies for dealing with these issues:

- *The experience-base of professionals without degrees could be extended by practice-oriented training programs that address key areas of advanced materials technology. This approach could significantly minimize the number and severity of problems associated with the introduction of new materials. Such a strategy might take advantage of programs offered by various technical societies.*

ALL SECTORS WORKING TOGETHER

Finding: Commercialization of materials would be facilitated by greater standardization of design data bases and development of international standards. Within the federal government, the National Institute of Standards and Technology is the agency most heavily involved in such endeavors. The institute's activities and workshops have emphasized the need for closer interactions between government and industry. It is clear that universities as well as professional societies have a contribution to make in the standardization of data bases, including the development of national and international standards. Since science, engineering, and technology emanate from many sources in the United States, it should not be surprising that the development of design data bases as well as standards is a pluralistic endeavor. Nevertheless, the competitiveness of the United States is suffering because of the uncoordinated nature of many of these efforts. The NMAB suggests the following strategies for dealing with these issues:

- *Development of materials standards, including international standards, is an essential aspect of building the infrastructure needed to support the commercialization of advanced materials. A federal agency, such as the National Institute of Standards and Technology, could establish a forum to develop the standards through timely, active participation by industry and other interested parties.*
- *Greater standardization of design-related materials properly data bases is necessary to facilitate the widespread application of new materials and thus increase the size and number of potential markets. The materials industry could lead this effort, with wide participation by government, universities, and professional societies.*

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