Materials Needs and R&D Strategy for Future Military Aerospace Propulsion Systems

Committee on Materials Needs and R&D Strategy
for Future Military Aerospace Propulsion Systems

National Materials and Manufacturing Board

Division on Engineering and Physical Sciences

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Preface

Significant advances in the performance and efficiency of jet and rocket propulsion systems are strongly dependent on the development of lighter, more durable high-temperature materials. Materials development has been significantly reduced in the United States since the early 1990s, when the Department of Defense (DOD), the military services, and industry had very active materials development activities to underpin the development of new propulsion systems. This resulted in significant improvements in all engine characteristics and established the United States at the leading edge of global propulsion technology.

In 2006, a study from the National Research Council (NRC) titled *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs* identified the need for technology advances in high-speed turbine engines, ram/scramjet/pulse detonation engines, rocket propulsion, combined cycle engines, and ultra-efficient propulsion to meet future military needs.[1] Each of the identified needs requires advances in propulsion technology, and those advances are strongly dependent on materials development activities. The DOD, the sponsor of the present study, thus identified the following tasks to be carried out by the present study committee (see Appendix A for the complete statement of task):

- Examine whether current and planned U.S. research and development efforts in materials for aerospace propulsion are sufficient (a) to meet U.S. military needs and (b) to keep the U.S. on the leading edge of propulsion technology.

[1] National Research Council. 2006. *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs.* Washington, D.C.: The National Academies Press.

- Consider mechanisms for the timely insertion of materials in propulsion systems and, if necessary, how these mechanisms might be improved.
- Consider mechanisms in place that retain intellectual property (IP) securely and how IP might be secured in future R&D programs.
- Describe the general elements of an R&D strategy to develop materials for future military aerospace propulsion systems.

To accomplish this study, the National Research Council established the Committee on Military Needs and R&D Strategy for Future Military Aerospace Propulsion Systems (see Appendix C for biographies of the committee members). The committee visited and received presentations from the sponsor, government research agencies, major propulsion companies, university researchers, and the American Institute of Aeronautics and Astronautics Materials Technical Committee, which covers the propulsion and materials science domains.

In addition, the committee was provided the document titled *Materials for Advanced Aerospace Propulsion and Power Systems* (AFRL-RZ-WP-TM-2008-2171). Restricted by the International Traffic in Arms Regulations (ITAR), that document contains the current plan for materials development within the Air Force Research Laboratory (AFRL) and was used as the baseline for current planned R&D efforts within the DOD. Owing to the restricted nature of that AFRL baseline document, the committee's specific assessment of current and planned U.S. R&D efforts in materials for aerospace propulsion is presented in an ITAR-restricted appendix (Appendix D), the text of which is not releasable to the public.

My personal thanks go to all of the members of the committee for their commitment of considerable time and energy. I am particularly grateful to Mike Hudson, Eric Jumper, Bob Latiff, Wesley Harris, and Sylvia Johnson for leading major segments of the study. The committee is also very grateful to Erik Svedberg, the study director, and to Teri Thorowgood, the administrative coordinator until December 2009, for guiding us through the study process. Erik Svedberg not only steered the committee but also provided valuable research contributions.

The committee hopes that this report will increase the efficiency, level of effort, and impact of DOD materials development activities. Budgetary restrictions demand increased collaboration and focus, as significant improvements in the performance and efficiency of U.S. military aerospace propulsion systems are both possible and needed.

George K. Muellner, *Chair*
Committee on Materials Needs and R&D Strategy
for Future Military Aerospace Propulsion Systems

Acknowledgments

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

Meyer J. Benzakein, Ohio State University,
Dianne Chong, The Boeing Company,
David E. Crow, University of Connecticut,
Alan Epstein, Pratt & Whitney,
Diana Farkas, Virginia Polytechnic Institute and State University,
Bernard L. Koff, Pratt & Whitney (retired),
James E. McGrath, Virginia Polytechnic Institute and State University,
Carolyn W. Meyers, Norfolk State University, and
Charles F. Tiffany, The Boeing Company (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Hyla Napadensky, retired vice president, Napadensky Energetics, Inc. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The committee also thanks its guest speakers, who added to the members' understanding of the materials issues related to future aerospace propulsion systems:

Joni Arnold, Air Force Research Laboratory (AFRL),
Drew DeGeorge, Edwards Air Force Base,
Kenneth Eickmann, University of Texas at Austin,
Joan Fuller, Air Force Office of Scientific Research (AFOSR),
William Hack, AFRL,
John Halchak, Pratt & Whitney Rocketdyne,
Dallis Hardwick, AFRL,
Clay Haubert, GE Aviation,
Joseph Koo, University of Texas at Austin,
Ajay Misra, NASA Glenn Research Center,
Francis Preli, Pratt & Whitney,
Tom Russel1, AFOSR,
David Schifler, Office of Naval Research,
Jack Schirra, Pratt & Whitney,
Charlie Stevens, AFRL,
Kathy Stevens, AFRL,
Art Temmesfeld, AFRL,
Malcolm Thomas, Rolls-Royce Group, and
Charles Ward, AFRL.

Contents

[1] Note that the text of Appendix D is not releasable to the public under ITAR.

Summary

Many of the significant advances in aircraft and rocket propulsion have been enabled by improved materials and materials manufacturing processes. Improving the efficiency and performance of a jet engine requires higher operating temperatures in order to improve thermodynamic efficiency. To improve efficiency further, engine weight must be reduced while preserving thrust. All of these improvements require new materials with higher melting points and greater strength and durability. Improvements in rocket casing and nozzle throat materials require similar advances. The development of lighter, more durable materials capable of operating at higher temperatures allows significant improvements in engine thrust to weight, fuel-use efficiency, and service life.

The period from about 1950 to 1990 in the United States produced significant advances in propulsion performance. That period was characterized by multiple military and commercial engine development programs, a robust group of engine companies and second-tier suppliers, and significant government investment in technology development, demonstration engines, and supporting infrastructure. Together these factors resulted in significant improvements in all engine characteristics and established the United States on the leading edge of propulsion technology.

THE MATERIALS DEVELOPMENT PROCESS

A three-step, tiered technology development process has been used in the U.S. Air Force (USAF) for years. Basic research (6.1), applied research (6.2), and advanced technology development (6.3) constitute the parts of the science and technology program that are managed by the Air Force Research Laboratory (AFRL). However, the National Research Council's Committee on Materials Needs and R&D Strategy for Future Military Aerospace Propulsion Systems, which conducted the present study at the request of the Department of Defense (DOD), found that although the tiered process is useful for budgeting purposes, development of materials technologies rarely adhere to the process, and technology maturation is driven more by the identification of a critical need or the sponsorship of a champion within the DOD or industry. In recent years, engine development cycles have been reduced and are considerably shorter than the development cycles for new materials. This mismatch in development timelines, coupled with a reduced infrastructure for engine development within government and industry, fewer development programs (transition opportunities), and increased aversion to risk by engine program managers, has decreased the support and advocacy for new materials development. The study found that this lack of support for new materials development has impacted the university environment. Structural materials education and research at U.S. universities have declined, and this decline in turn will threaten the viability of the domestic structural materials engineering workforce.

The bottom line, according to this report, is that the current approach to developing new materials, at low levels of maturity, is inadequate for today's environment with reduced infrastructure, fewer transition opportunities, increased risk aversion, and limited advocacy and funding.

MATERIALS DEVELOPMENT ASSESSMENT

The DOD and the AFRL have in the past been able to provide the USAF and U.S. industry with a global competitive advantage in materials and propulsion technology and fielded systems. However, current and future planned AFRL engine programs have a decreased level of industrial-base cooperation and materials funding. It appears that the transition from basic research, to applied research, to advanced technology development, to the manufacturing of technology is not characterized by a formal, executable process, but rather is conducted on an ad hoc basis responding to "user pull" and short-term competitive imperatives.

The current planning processes of the AFRL Materials and Manufacturing Directorate and Propulsion and Power Directorate are evolving to address AFRL's Focused Long Term Challenge (FLTC) approach. The AFRL recognizes the need for activities in the near term, intermediate term, and far term to address the full spectrum of the Air Force mission; however, the expanded scope of the Air Force mission has put significant pressure on the far-term propulsion materials funding profile. The committee believes it is essential that a balance be maintained between the near-term, intermediate-term, and far-term activities in response to the FLTC demands on the one hand, and a long-term concomitant funding commitment on the other.

In addition, the decline that has occurred in the number of technology demonstrators has significantly reduced the number of opportunities to demonstrate advanced materials and processes prior to their insertion into existing and emerging propulsion systems. Although the number of planned new systems is limited, advanced materials are critical in improving existing and emerging propulsion systems to meet stated military needs. The committee believes that the AFRL's Materials and Manufacturing Directorate and Propulsion and Power Directorate will achieve more value for their investments by increasing their communication and collaboration with the Air Force Office of Scientific Research (AFOSR), the system program offices, and industry relative to propulsion materials advances, technology readiness, and the potential payoffs of technology insertion.

GLOBAL MATERIALS DEVELOPMENT ENVIRONMENT

The committee conducted an open-source assessment of global materials development activities. Since the early 1990s, there has been significant investment in materials development within Europe, Russia, and Japan. The European Union established the European Technology Platform on Advanced Engineering Materials and Technologies (EuMaT).[1] That organization facilitates advanced research in the development and application of advanced engineering materials and related manufacturing processes. Specific activities are funded through the contribution of industry (target: 35 percent), national governments (target: 35 percent), and the European Commission (target: 30 percent). The EuMaT strategic plan indicates funding of 4 billion euros for advanced materials development, with yearly allocations ranging from 500 million euros to 2.0 billion euros. All development activities involve consortia of industry, government, and university researchers.

Similar advanced materials research continues within Russia and the Ukraine and is frequently conducted in partnership with European Union researchers. Japan makes use of partnerships hosted by its national laboratories to conduct materials research. These partnerships involve one or more industry participants and university researchers. Japan has become a world leader in high-temperature materials made of ceramics and ceramic-matrix composites.

The committee identified several areas in which the United States is not at the leading edge of propulsion technology. Specifically, the United States has lost competitive advantage in the following areas: the attachment of the compressor and fan blades using advanced welding processes, superplastically formed diffusion-bonded hollow fan blades, and some areas of ceramic-matrix composites. In most

[1] Information on EuMaT is available at http://www.eumat.org/. Accessed December 16, 2009.

cases, this loss of competitive advantage is the result of the limited funding of U.S. research efforts and of consortia activities elsewhere in the world. Unfortunately, the loss of competitive advantage with respect to these technologies will result in a competitive disadvantage for U.S. suppliers.

In order to maintain or regain the U.S. competitive advantage in the areas of propulsion materials and keep the United States on the leading edge of propulsion technology, there is a need to increase activities in new materials development and competitive 6.2 component and 6.3 demonstrator programs related to materials development and to pursue collaborative research activities within this very competitive global environment.

INTELLECTUAL PROPERTY AND EXPORT CONTROL

Collaboration between competing companies, focused principally on pre-competitive research, has led to numerous successful developments that benefit both the collaborating engine companies and, arguably, the entire materials community. It remains essential in such collaborative arrangements that engine producers safeguard pre-existing competition-sensitive information and intellectual property (IP) and that these collaborative agreements between competing companies fairly distribute or share newly developed IP and data rights. The committee found that this has been successfully accomplished within existing IP protection mechanisms found within export controls.

Significant global investment in materials technologies has led to a highly competitive global environment. Future U.S. access to foreign world-class propulsion materials technology may be difficult or impossible to obtain, thereby impacting the U.S. ability to achieve advanced propulsion system capabilities. Delays and uncertainties associated with International Traffic in Arms Regulations (ITAR) requirements hamper and discourage international collaboration on research for propulsion materials.

ELEMENTS OF AN EFFECTIVE RESEARCH AND DEVELOPMENT STRATEGY

The following 10 elements are listed in an approximate order of importance; clearly, the importance of different elements can change with specific circumstances.

1. Annual reviews of the Air Force propulsion materials requirements, objectives, and execution plans to adjust for budget changes and the external environment.

2. Better integration of AFOSR programs into Air Force propulsion materials plans and more involvement of academia and industry in the development of the plans.
3. The development of a stable, long-term materials development program that covers basic research through manufacturing and has provision for materials insertion into test engines.
4. The development of a sufficiently robust and, most important, a stable funding stream.
5. The continued development of Integrated Computational Materials Engineering (ICME) approaches that promise to shorten the materials development time.
6. The implementation of a systems engineering approach to propulsion materials development that includes a risk management plan aimed at inserting materials considerations early in any engine development program.
7. The use of existing engines and demonstrators to expedite materials insertion and technology maturation.
8. The inclusion of academia in transition research and development (R&D) both to take advantage of talent and facilities that exist at selected universities around the country and to ensure the development of the required workforce.
9. The increased use of government-industry-academia partnerships to conduct pre-competitive R&D.
10. The integration of foreign technology development and research with U.S. efforts. Opportunities for collaborative fundamental research should be pursued.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the committee found that the U.S. current and planned R&D efforts are not sufficient to meet U.S. military needs or to keep the United States on the leading edge of propulsion technology.

The United States has had a demonstrated process for developing state-of-the-art materials for propulsion systems, but that process needs to be updated to accommodate today's development environment. Previous best practice for developing new materials depended on a defined propulsion system need, demonstrator engines to verify the materials, and consortia of government, academia, and industry to develop the materials. The current plan is lacking in many of these areas. The U.S. development environment is far less robust than in the past, and significant global investment has produced a very competitive environment. The committee found that in several key technology areas (ceramics, joining processes, and superplastic bonded, hollow fan blades), Europe or Japan is establishing the leading edge of propulsion technology. Additionally, Japan and France are the dominant producers of carbon-carbon fiber that is used both in lightweight structures and in high-temperature carbon silica composites. There are no U.S. domestic sources for these materials.

Although the number of new engine development programs in the United States has decreased, opportunities still exist to transition new materials into existing engines in order to improve performance, efficiency, or durability. The committee identified several challenges in materials development that must be met in order to satisfy military needs. These include the following three:

1. Currently, gas turbine efficiency, higher thrust-to-weight ratios, and operation at maximum Mach numbers are limited by compressor disk materials—that is, the 1300°F limit of the compressor disk materials confines the maximum gas turbine pressure ratio to 50 to 1, although higher pressure ratios would remove all of the above limits.
2. Hydrocarbon-fueled scramjets are limited to approximately Mach 8 by the heat absorption of hydrocarbon fuel. Ceramic structures or better thermal barrier coatings are required to remove this limitation. The higher heat sink afforded by hydrogen fuel allows hydrogen scramjets to achieve approximately Mach 12. The materials above would also raise this limit.
3. Rocket engines are limited by fuel/oxidizer velocities. Higher pressure ratios and lower-weight structures are needed to improve rocket engine effectiveness.

In addition, the Versatile Affordable Advanced Turbine Engine (VAATE) Program could offer increased transition opportunities if better coordination occurred among the AFOSR, AFRL, industry, and academia. The committee found numerous examples of government-industry-academia consortia performing pre-competitive development activities without hindering industry's ability to protect key intellectual property in the later phases of materials and process development. Because the United States trails Japan and Europe in some key propulsion materials areas, it is important that laws and practices allow the inclusion of these leading-edge areas of materials development in new government and industry consortia. DOD funding agencies should identify and support, both financially and through regulatory and administrative relief, opportunities for pre-competitive collaborative research for structural propulsion materials, both domestically and with global partners.

The committee makes the following recommendations:

- The Air Force Research Laboratory's Materials and Manufacturing Directorate and Propulsion and Power Directorate need to develop a strategy to maintain or regain U.S. preeminence in propulsion materials. The strategy should include the regular review and updating of the directorates' propulsion materials plan, with an emphasis on the consequences of unfunded items, the changing external environment, and maintaining a balance for the near-, mid-, and far-term activities in response to the Focused Long Term Challenges and funding commitment.

- The strategy for developing future aerospace propulsion materials should define a materials development program with stable and long-term funding. The program should cover basic 6.1 research through 6.3 development and include manufacturing and insertion strategies. It should involve industry, academia, and other government entities, and it should selectively consider global partners for pre-competitive collaboration. Essential elements of the strategy include a steering committee, feedback metrics, and a risk reduction plan based on systems engineering practices.
- The AFRL's Materials and Manufacturing Directorate and Propulsion and Power Directorate should increase their communication and collaboration with the AFOSR, system program offices, industry, and academia relative to propulsion materials needs, advances, technology readiness, and the potential systems payoffs of technology insertion.
- To maintain or regain the U.S. military competitive advantage in the areas of propulsion materials and to keep the United States on the leading edge of propulsion technology, there is a need for advocacy within the Office of the Secretary of Defense/Director, Defense Research and Engineering, to increase activities in new materials development and competitive 6.2 component and 6.3 demonstrator programs.
- The U.S. State Department should reformulate the ITAR fundamental research exclusion to encompass all such research whether performed in academia, industry, or government. This exclusion should also apply to fundamental research activities encompassed within larger research programs that contain other ITAR-controlled elements.
- DOD funding agencies should identify and support, both financially and through regulatory and administrative relief, opportunities for pre-competitive collaborative research for structural propulsion materials, both domestically and with global partners.
- For the special case of pre-competitive research with global partners, the DOD, the Department of State, and other U.S. government entities, including the Department of Commerce, should proactively encourage such pre-competitive research opportunities and develop ways to facilitate knowledge transfer within wide, acceptable boundaries.
- The research activities of the Air Force Office of Scientific Research should tie more closely to AFRL propulsion materials needs so as to provide a path

to insertion. Together the AFOSR and the AFRL should develop a research portfolio that covers a wider range of near-, mid-, and far-term needs.
- The United States should continue to develop computational methods to shorten materials development time and to reduce the time required for testing and materials validation so as to reduce the risk related to insertion of new materials.
- The Air Force should fully implement the R&D strategy that it develops, and it should reevaluate its strategy annually.

THE WAY AHEAD

For many years the United States has defined the leading edge of propulsion and propulsion materials technology. This technology has provided the nation with a military and commercial competitive advantage. Due to changing priorities, atrophying infrastructure, and a much more competitive global environment, the United States must take action to regain its competitive position.

1

Introduction

1.1 BACKGROUND

The ongoing development of military aerospace platforms requires continuous technology advances in order to provide the nation's warfighters with the desired advantage. In 2006, a report entitled *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs* from the National Research Council's (NRC's) Air Force Studies Board (AFSB) concluded that airplane propulsion systems designed to approach Mach 5 would require the development of materials technology solutions that are as yet unavailable.[1] A related 2006 AFSB report, *Future Air Force Needs for Survivability,* describes challenges to improving propulsion and signature, or stealth, that are materials-intensive and must be addressed if the Air Force, and the other services by extension, are to move ahead toward the development of high-Mach manned or unmanned air vehicles.[2]

The NRC's 2006 *Aerospace Propulsion Needs* report concluded that "additional emphasis must be placed on propulsion research or the technological lead of the United States will almost certainly cease to exist."[3] It also concluded that the way forward for the materials technology development base is still not fully defined

[1] National Research Council. 2006. *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs.* Washington, D.C.: The National Academies Press.

[2] National Research Council. 2006. *Future Air Force Needs for Survivability.* Washington, D.C.: The National Academies Press.

[3] National Research Council. 2006. *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs.* Washington, D.C.: The National Academies Press, p. 26.

and that top priority should be given to overcoming the technology barriers that will have the largest impact on future weapons systems. As indicated in that report, these barriers include the following: compressor discharge temperature limits; turbine inlet temperature limits; high-temperature, high-heat-sink fuels for thermal management; lightweight structures; and signature control.

The technology challenges in developing future military aerospace propulsion systems are significantly materials challenges. Overcoming these challenges will require focus on a systematic materials approach and materials R&D specific to the needs of the subsystem involved. Such considerations would include the following:

- Materials for atmospheric propulsion systems, both air-breathing and alternate systems;
- Materials for space propulsion systems;
- Materials for alternative fuel engines;
- Materials for the development of lightweight and multifunctional systems;
- Materials methodologies for stealthier (signature controlled) systems; and
- Strategies to coordinate the development of materials, composites, and interactive materials systems that will work together to create an effective and efficient multifunctional materials palette.

These materials issues will require that the DOD take new R&D directions and, in that context, the NRC was asked by the DOD to conduct the present study to assess the needs and directions for a national materials R&D strategy to respond to the challenge of developing materials for future military aerospace propulsion systems and to keep the United States on the leading edge of propulsion technology.

1.2 FUTURE MILITARY AEROSPACE PROPULSION NEEDS

Capabilities-based planning addresses the uncertainty in the threat environment by using a wide range of scenarios to bound requirements for future systems. The DOD introduced this approach several years ago as the planning approach to be used for justifying military needs, but at the present time this planning approach is not sufficiently mature to have identified stated needs. However, the 2006 NRC study referred to above—*A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs*—identified global strike, global mobility, airborne C4ISR (command, control, communications, computers, intelligence, surveillance, and reconnaissance), and next-generation space access as required capabilities. These capabilities require technology advances in high-speed turbine engines, ram/scramjet/pulse detonation engines, rocket propulsion, combined-cycle engines, and ultra-efficient propulsion. Therefore, the committee used these capabilities as the required system improvements for the purposes of this study.

Each of these required advances in propulsion technology is strongly dependent on materials development activities. Improving the efficiency and performance of a jet engine requires higher operating temperatures in order to improve thermodynamic efficiency. To improve efficiency further, engine weight must be reduced while preserving thrust. All of these improvements require new materials with higher melting points and greater strength and durability. Similar advances are required in rocket casing and nozzle throat materials. To address these required advances, the DOD identified the tasks listed in the following section to be carried out by the present study, conducted by the NRC's Committee on Materials Needs and R&D Strategy for Future Military Aerospace Propulsion Systems.

1.3 STATEMENT OF TASK

The statement of task for this study is as follows:

The committee will:

- Examine whether current and planned U.S. R&D efforts in materials for aerospace propulsion are sufficient (a) to meet U.S. military needs and (b) to keep the U.S. on the leading edge of propulsion technology.
- Consider mechanisms for the timely insertion of materials in propulsion systems and, if necessary, how these mechanisms might be improved.
- Consider mechanisms in place that retain intellectual property (IP) securely and how IP might be secured in future R&D programs.
- Describe the general elements of an R&D strategy to develop materials for future military aerospace propulsion systems.

The committee will consider both air breathing and self contained fuel/oxidizer systems including scramjet capabilities and take account of: (a) fuel-efficiency and materials-technology challenges at both subsonic and supersonic (up to Mach 5); (b) findings and recommendations in the recent NRC report entitled *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs* issued in 2006; (c) the impact of current non-U.S. investments in propulsion materials technologies; (d) the lead time for insertion of new materials into aerospace propulsion technologies and what would it take to shorten the timeline, if it is too long and (e) the evolution of U.S. R&D on materials for aerospace propulsion with due consideration of:

- Historic funding levels;
- Government agencies involved;
- Government investments (for both defense and civil applications) and industrial investments in propulsion R&D; and
- Outside drivers such as non-defense and non-NASA investments and needs.

1.4 METHODOLOGY

To fulfill its statement of task, the committee held five meetings (see the "Acknowledgments" section in the front matter of this report for a list of the committee's guest speakers) and made a site visit to the AFRL Propulsion and Power Directorate at Wright-Patterson Air Force Base in Ohio. The committee received presentations from the sponsor and government research agencies, key industry participants in the propulsion and materials science domains, and academics from the materials science and metallurgy fields, as well as from General Kenneth Eickmann, chair of the 2006 NRC study *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs*.

In addition, the committee was given access to a document titled *Materials for Advanced Aerospace Propulsion and Power Systems* (AFRL-RZ-WP-TM-2008-2171). Restricted by the International Traffic in Arms Regulations (ITAR), that document (hereinafter referred to as the plan) contains the current plan for materials development within the AFRL and served as the point of comparison for the committee's first task (see the preceding section), which requires an assessment of "whether current and planned U.S. R&D efforts in materials for aerospace propulsion are sufficient (a) to meet U.S. military needs and (b) to keep the U.S. on the leading edge of propulsion technology."

The committee addressed the statement of task in the following manner. Chapter 1 presents the origin and background of the study. Chapter 2 addresses the process of materials development and the second task. The first task is addressed in Chapter 3, and the committee's specific assessments of the AFRL plan are included in Appendix D, the content of which is governed by ITAR/Export Administration Regulations restrictions and so is not included in the publicly released version of this report. Chapter 3 also contains a limited assessment of international materials development efforts, to aid in the determination of which nations are near the "leading edge" of propulsion technology. The issue of intellectual property protection is covered in Chapter 4, which addresses the third task. Chapter 5 outlines the recommended path forward by describing the key elements of an effective R&D strategy, addressing the fourth task.

Appendix A presents the committee's statement of task. Appendix B provides an overview of the work being done throughout the world at the leading edge of aerospace propulsion as described in open-source literature. Appendix C presents the biographies of the committee members. The text of Appendix D, which contains the committee's ITAR-restricted analysis of the current plan for materials development within the AFRL, is not releasable to the public under ITAR. Appendix E offers some materials development case studies. Appendix F defines the acronyms used in this report.

2

Materials Development: The Process

2.1 INTRODUCTION

A three-step, tiered technology development process has been used in the U.S. Air Force (USAF) for years. It is taught at the Defense Acquisition University as part of the science and technology (S&T) management courses and instantiated in Department of Defense (DOD) and Air Force regulations.[1] Air Force acquisition regulations assign responsibility for the execution of S&T, the assessment of technology readiness level (TRLs), and the negotiation of technology transition agreements. The majority of these responsibilities fall on the Air Force Research Laboratory Commander.[2]

Unfortunately, despite the fact that this three-step development process is instantiated in the planning and budgeting process, it rarely executes as published. Funding changes, advances or delays in moving to higher TRLs, and the dynamics of the technology-push–requirements-pull relationship result in each technology's maturation path being different. In contrast to this notional model (further discussed in Section 2.4, below), what has actually occurred with respect to the technology development process cannot be well defined, differs from one case to the next, and, most importantly, changed substantially toward the end of the 1980s.

[1] Air Force Instruction, AFI 63-101. Available at http://www.af.mil/shared/media/epubs/AFI63-101.pdf. Accessed July 9, 2009.

[2] Donald C. Daniel, Center for Technology and National Security Policy. 2006. "Issues in Air Force Science and Technology Funding." National Defense University, Fort Lesley J. McNair, Washington, D.C., February.

That change involved an increased emphasis on risk reduction and on decisions made by reliance on TRLs—considerations that now drive materials selection in engine developments (including demonstration engines) to the point that the insertion of new materials appears only tangentially in the objectives of engine test programs. Along with this paradigm shift, the evolutionary advance of traditional turbine materials, such as superalloys, has slowed. Engine designers have become averse to the increased risk of materials insertion, and so not only have once-widespread evolutionary materials and process discoveries decreased, but the funding for needed underlying developments has also been downplayed by the new paradigm change. This sentiment was expressed, for example, at the workshops leading to publication of the National Research Council (NRC) report *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems,* which stated, "Workshop speakers unanimously identified risk aversion as a fundamental barrier to innovation and rapid technology transition."[3] This idea can be recast as follows: More stringent DOD guidelines with respect to required TRLs for incorporation of technology drive the engine OEMs (original equipment manufacturers) to proven low-risk technologies.[4] At the same time, the path to quantum changes in advancements (discussed in Section 2.3, below) appears to point toward revolutionary classes of structural materials such as ceramic-matrix composites (CMCs) for which even less of a technology base is available. The lack of data for these materials predisposes risk-averse engine designers to avoid their use. These "structural" changes in the process for the development of new materials for propulsion have also been accompanied by a distinct change in the character of materials programs at U.S. universities.

All of these elements are crucial to the understanding of why things are as they are at the present time and what might be done to adapt to and perhaps improve the present state of advances in structural materials for propulsion. Understanding the notional process and what has actually occurred depends on understanding TRLs and funding definitions. These are discussed in Section 2.2, below, followed by a brief discussion in Section 2.3 of the critical role that materials development has played in advancing turbine engine performance. In Section 2.4, the nominal materials development process for propulsion materials is described. These sections are meant to place in better perspective the pre-1990s' materials development "process"; Sections 2.5 and 2.6 then discuss how this process evolved in the changing 1990s' environment into the present development process. Major programs that have contributed to advances in propulsion structural materials

[3] National Research Council. 2004. *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems.* Washington, D.C.: The National Academies Press, p. 19.

[4] This observation was made by project managers in the AFRL Propulsion and Power Directorate, during presentations to the committee at Wright-Patterson Air Force Base, Ohio, May 27, 2009.

are outlined in Section 2.7; these programs were started at the beginning of the paradigm shift in the process and continue to the present with the new demonstrator-engine program, the Versatile Affordable Advanced Turbine Engine (VAATE) Program. Section 2.7 ends with a discussion of the characteristics of successful materials development programs. Section 2.8 describes the common themes for successful materials development. Section 2.9 discusses the evolution of materials science and engineering programs at U.S. universities. Section 2.10 discusses the Air Force Office of Scientific Research (AFOSR). Finally, the chapter closes in Section 2.11 with a list of findings supported by the discussion in the chapter. These findings should be helpful in providing the context for Chapter 3, an assessment of the present state of materials development. As importantly, these findings form the starting point for Chapter 5, which presents discussion of and recommendations for a way forward.

2.2 TECHNOLOGY READINESS LEVELS AND RESEARCH AND DEVELOPMENT FUNDING

As mentioned above, a certain level of understanding of how risk is assessed and what types of funding are being used in DOD research and development (R&D) is needed for a discussion of the evolution of the process of materials development for propulsion. This section briefly describes these topics.

2.2.1 Technology Readiness Levels

Technology readiness levels are used by U.S. government agencies to define the level to which a technology has been developed and the concomitant risk associated with attempting to incorporate the technology into a development program. Readiness levels are also used in industry in one form or another, although the descriptions used by industry may differ from those used by the government. It is generally possible to align a company's readiness level with the government's definitions; when a TRL is mentioned in this chapter, an attempt is made to use the government's definition. Even so, over the years TRLs have diverged slightly in definition between those of the DOD and of NASA. The definitions of the levels used by the DOD are given in Table 2.1.

2.2.2 Definition of DOD Defense Research and Development Funding

The DOD has 11 major force programs in which program 6 is for research, development, testing, and evaluation. Program 6 is further divided into five subcategories; see Figure 2.1. The subcategories for DOD research and development funding are referred to as 6.1, 6.2, and 6.3:

TABLE 2.1 Technology Readiness Levels in the Department of Defense (DOD)

Technology Readiness Level	Description
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated. Invention begins.	Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that the pieces will work together. This is "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and "flight qualified" through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system "flight proven" through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.

SOURCE: Reprinted from Department of Defense, 2006, *Defense Acquisition Guidebook and Technology Readiness Levels,* Washington, D.C.

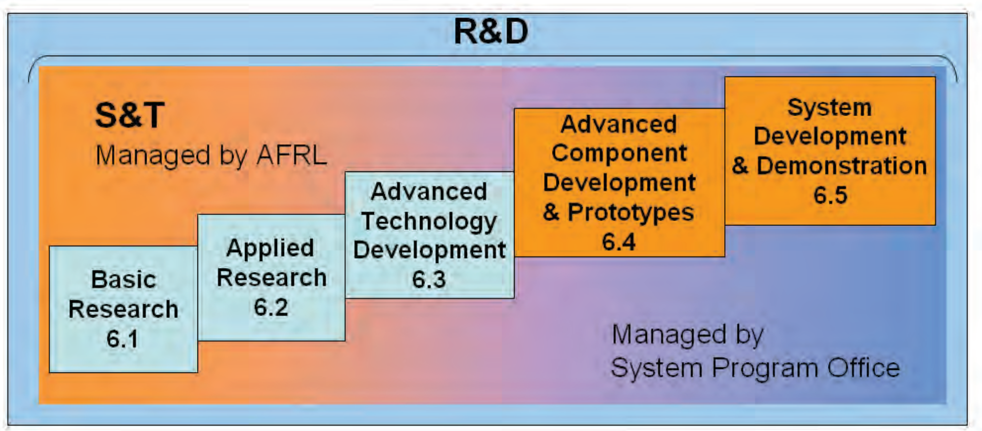

FIGURE 2.1 The 6.1 to 6.5 ladder: subcategories in Department of Defense program 6 for research, development, testing, and evaluation. SOURCE: Air Force Research Laboratory (AFRL).

6.1 basic research includes scientific study and experimentation to increase knowledge and understanding in science and engineering related to long-term defense needs. This research provides the foundation for technological improvements to warfighting capability.

6.2 applied research includes efforts to solve specific defense problems, short of major developments or demonstrations. This applied research category includes the development of components, models, and new concepts through in-house and industry efforts. Individual research programs often enable a variety of new systems and support a number of identified needs.

6.3 advanced technology development includes all efforts directed toward projects that have moved into the demonstration of hardware or software for operational feasibility. Experimental systems or subsystems are demonstrated in order to prove the technical feasibility and military utility of the approach selected. Advanced technology development (6.3) provides the path for the rapid insertion of new technologies or product improvements into defense systems.

Continued R&D efforts beyond 6.3 require special funding aimed at the development of engine demonstrators, specific engine component developments, or support of new weapon systems or subsystems.

2.2.3 Technology Readiness Levels and Funding Definitions

Technology readiness levels are aligned with funding levels in Figure 2.2. This alignment was provided by the Materials and Manufacturing Directorate of the

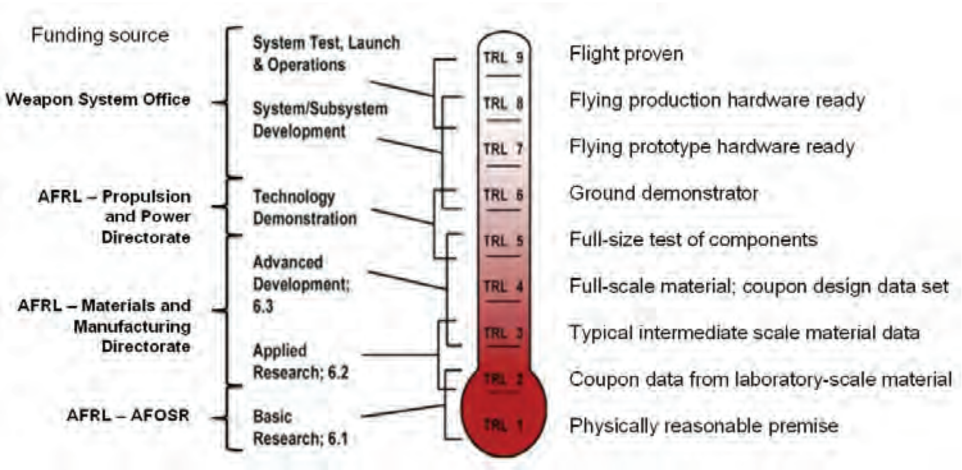

FIGURE 2.2 Alignment of technology readiness levels (TRLs) with funding levels as applied to materials for propulsion. NOTE: Acronyms are defined in Appendix F. SOURCE: Materials and Manufacturing Directorate of the Air Force Research Laboratory, October 2009.

Air Force Research Laboratory, applied to materials for propulsion, and is current as of this writing. When comparing the definitions of TRLs with the purported intent of the funding levels as seen in Figure 2.2, it is clear that this alignment is somewhat subjective and could be altered.

The subjectivity in defining research funding levels is clearly not limited to this particular case. In dealing with other directives within the government, the term "fundamental research" is used to cover a range of research levels and funding levels. In National Security Decision Directive 189 (NSDD 189), for example, "fundamental research" means basic and applied research in science and engineering, the results of which ordinarily are published and shared broadly within the scientific community, as distinguished from proprietary research and from industrial development, design, production, and product utilization, the results of which ordinarily are restricted for proprietary or national security reasons. Thus it is clear that the level of funding that can be interpreted as "fundamental research" is not restricted to 6.1 funding and can be the result of 6.2 and even 6.3 funding.

2.2.4 Technology Demonstration: Definitions of Milestones A, B, and C

Once funding moves beyond 6.3 (see Figure 2.2) to support TRLs above 5 and 6 through technology demonstrations, the Defense Acquisition System uses the concepts of Milestones A, B, and C, which may be thought of as gates in a system development process. Concept development and refinement occur before

Milestone A, and further technology development to work out the concept occurs before Milestone B. Only after Milestone B does a program become an enterprise with dedicated funding behind it; the nature of systems engineering thus changes significantly after Milestone B. Figure 2.3 illustrates the milestones in conjunction with the technical review timing.

These milestones can also be aligned with TRLs. Milestone B occurs at approximately TRL 6. Recall that at TRL 6, any new material must be at the point where a representative or prototype component has been tested in a relevant environment and is ready to be made into an actual prototype to be tested in an actual system environment. Without providing an exact definition of Milestone B, it can be said that its focus is a demonstration of process maturity and component development. Milestone B generally marks the end of 6.3 programs, which start at TRL 3 or 4.

The major review for engineering acquisition at Milestone B is aimed at managing the risk for further development. This generally means that materials must be selected early in the process, because the use of new materials may require new designs and increase risk. By whatever process, a new material must have been matured to approximately TRL 5, bridging an ill-defined gap often described as the "valley of death." The valley of death is associated with a disconnect between

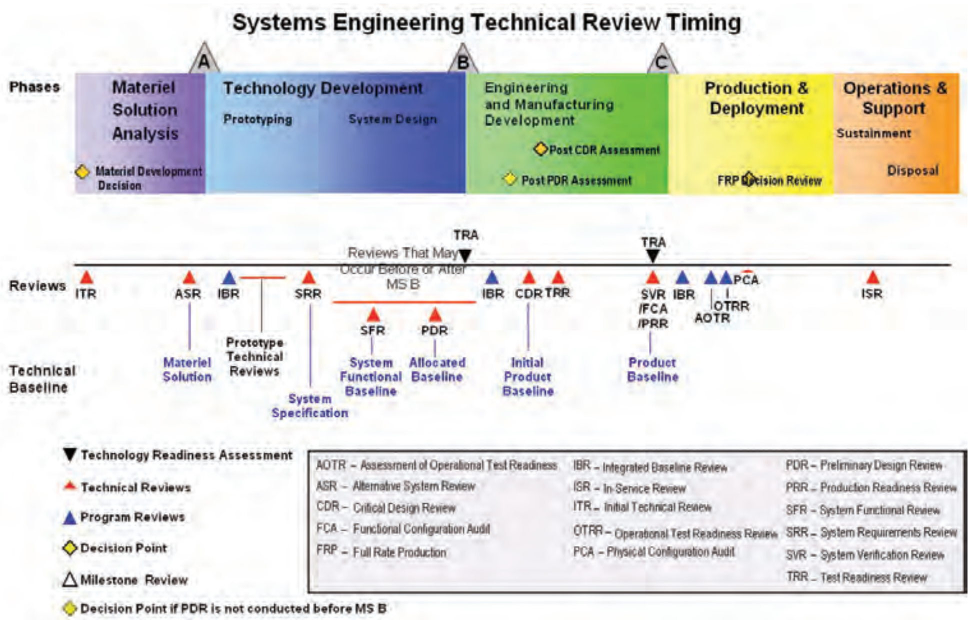

FIGURE 2.3 Milestones A, B, and C for systems engineering review. SOURCE: Reprinted from Figure 4.3, Chapter 4, p. 39, of *Interim Defense Acquisition Guidebook.* Available at https://acc.dau.mil/dag.

technology development and successful application; it has been the subject of many books, studies, and discussions. The NRC report *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems* discusses the issue extensively.[5] Overcoming this barrier requires understanding the issues associated with it and devising strategies to be more successful in bridging the barrier. Much of the information in this report is applicable to the question of determining the adequacy of strategies for continued progress in developing materials for propulsion.

2.3 THE ROLE OF MATERIALS IN THE ADVANCEMENT OF PROPULSION TECHNOLOGY

Although it goes without saying that materials technology, including the development of materials and the processes to turn these materials into engine components, has contributed significantly to the advance of propulsion technology over the past six decades, a brief discussion of this point may be helpful. The advent of new materials and processes (M&P), such as vacuum melting, high-strength titanium alloys, and superalloys, has enhanced materials performance, enabling increased turbine temperatures, rotor speeds, and engine thrust at ever-increasing engine efficiencies. This advance for high-pressure turbine airfoils is chronicled in Figure 2.4, which shows how materials improvements in concert with innovative turbine blade design advances have increased turbine inlet temperatures by a factor of two between 1940 and 2006. Complementary advances for structural titanium and superalloy rotor materials have enabled increases in rotor speed and thrust.

Figure 2.4 also includes a projection of possible avenues to further enhance performance if materials advances continue, but it should be noted that at present the VAATE Program (discussed in Chapter 3) is not funded to develop components with the new materials concepts indicated on the figure. Today, the array of materials that are being used for propulsion or that may possibly be used in future systems is both vast and diverse, representing all classes of structural materials, including metal alloys, intermetallics, ceramics, polymer-matrix composites, metal-matrix composites, and ceramic-matrix composites. The fact is that turbomachinery continues to depend predominantly on wrought or cast metallic alloys for the majority of engine components. The latter, nonmetallic materials clearly have the potential to contribute to future propulsion advances; however, the successful insertion of these advanced materials will depend on a thorough understanding of these emerging material classes and an acknowledgment of attendant manufacturing and durability risks.

[5] National Research Council. 2004. *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems.* Washington, D.C.: The National Academies Press.

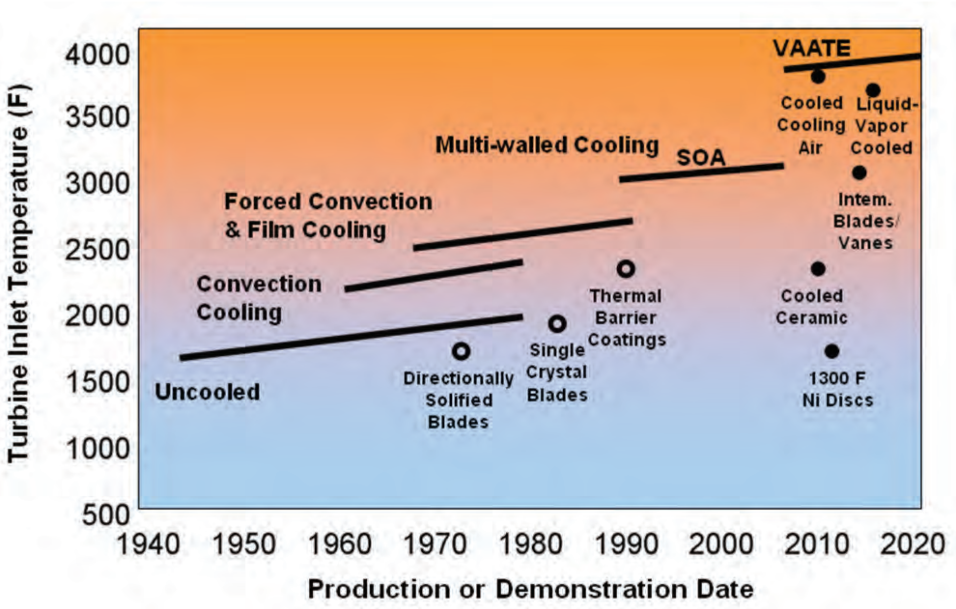

FIGURE 2.4 The complementary contribution of materials advance and innovative design engineering on turbine inlet temperature increases over the past six decades. NOTE: Acronyms are defined in Appendix F. SOURCE: Information from a presentation to the committee by Charles Ward, Air Force Research Laboratory, January 2009. Approved for unlimited distribution: Public Affairs Case Number 88ABW-2009-0180.

Over the past six decades, continued advances in materials both enabled new Air Force systems with greater efficiency and performance and transitioned to U.S. aerospace companies, which continued to have competitive advantages. Now, however, continued investments by the Air Force and the DOD in the work needed to mature these new advanced materials to the point that they play a role in future engine advances[6] appear to be downplayed. In general, this is because people appear to associate the need for continued advances in structural materials for propulsion systems with the expectations of new airframe programs in the Air Force—in this case there is a declining expectation, an expectation of fewer new airframe programs in the Air Force. However, this apparent association overlooks the role of advanced materials in upgrading existing engines. As an example, the benefits of continued technology insertion in fielded engines are well illustrated by the continued development of the PW100 and the GE110 engines. Technology insertion allowed these engines to have significant performance and durability

[6] Personal communication, C. Ward, AFRL, and C. Stevens, AFRL, May 2009.

enhancements, resulting in the improved-performance engines that powered the F-15E and the later sections of the F-16 engine.

If materials development is to continue to play its historically demonstrated role in advancing engine performance, some enhanced investment will likely be needed. However, it is important to understand where this investment might best be placed, and this in turn depends on an understanding of the process that a new materials development goes through from concept to insertion.

2.4 THE NOTIONAL DEVELOPMENT PROCESS FOR PROPULSION MATERIALS FROM IDEA TO INSERTION

As discussed in Section 2.5, below, the introduction of new materials into a new or demonstration engine rarely follows the specified model. But regardless of whether or not the model is followed, it is important to discuss it because it is clear that funding plans are made under the assumption that this notional development plan *will* be followed. The time period from the point of the introduction of a new material idea to the point at which it is seriously considered for insertion into an engine involves a long-term process that can exceed 20 years. But rather than specifying time in years, it is easier here to describe a notional process with a "timeline" in TRLs. The notional timeline given in Figure 2.5 indicates a continuous maturation of a single material from a large number of initial candidates being nurtured at the 6.1, TRL 1 level of funding and readiness. In general, funding requirements at the lowest TRL level, even for a large number of good ideas, are small compared to the costs of insertion in the final stages of development of, by then, a single material. The funding requirements are also notionally described in Figure 2.6 as a companion to Figure 2.5. As one or a few of the ideas progress into further development, during which coupons are actually produced and property information is beginning to be obtained, the cost increases above the levels provided for all of the basic-concept materials. As larger scale-up occurs, representative geometries are reduced and spin tests and other tests are run on even fewer ideas, the costs escalate again, eventually rising to a level of risk that allows a single material to be matched against a conceptual design in pre-Milestone A, TRL 4 to 5 (see the discussion of milestones, above). Finally a Milestone B point is reached, and full-scale development begins.

It is difficult to ascribe actual years along the timeline axis in Figures 2.5 and 2.6, but Table 2.2 is helpful in this regard. Table 2.2 describes the nominal number of years required to bring a new material to the maturity level needed for insertion, depending on the level at which the material development starts. It is probably possible to match the "Development Phase" description in the table with a TRL level; however, for the purpose of this description, it is assumed that the TRL for the shortest development time is approximately TRL 5 or 6. At the longest devel-

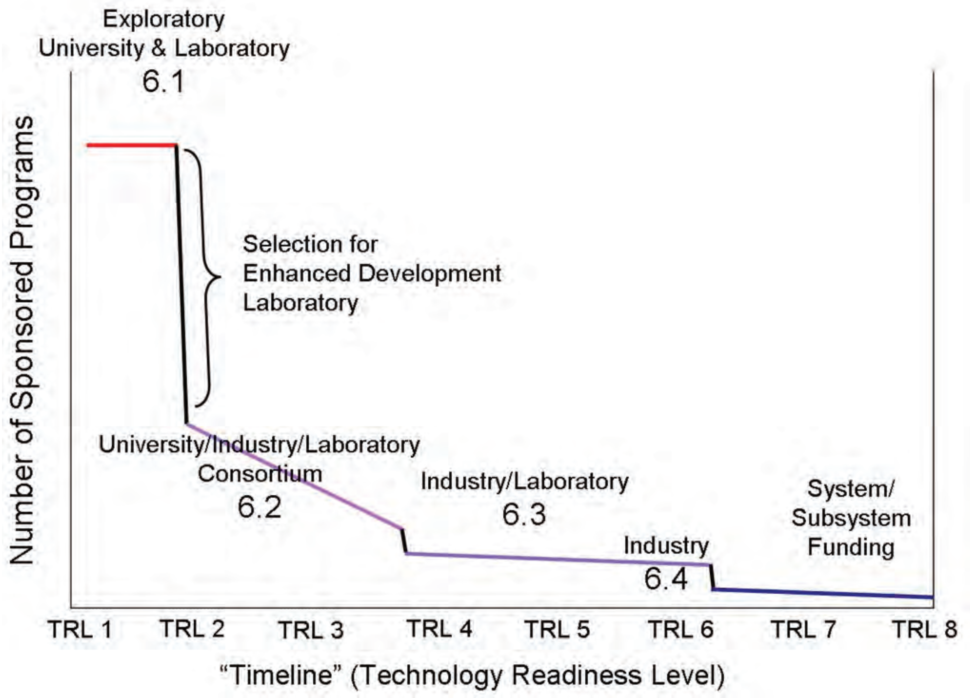

FIGURE 2.5 Notional development technology readiness level (TRL) timeline.

opment time, the TRL level is approximately TRL 1. In this regard then, one can assume that the timeline extends to 20 years or more.

Section 2.5 describes how structural materials are actually brought into the engine development cycle and concludes that in order for quantum increases in performance to be made, new classes of materials beyond wrought or cast metallic alloys must be considered. If the notional process described in Figure 2.6 were to exist, however, ensuring a continuous flow of materials into new engine developments would require, as shown in Figure 2.7, that a new cycle for each new material or class of materials was reinitiated on a continuing basis.

2.5 THE HISTORICAL MATERIALS DEVELOPMENT PROCESS: HOW IT HAS ACTUALLY WORKED

Rather than closely following the prescribed process described in Section 2.4, the development and application of new propulsion structural materials have historically either opportunistically exploited novel and independent discoveries or have had programs established in order to use evolutionary developments in composition,

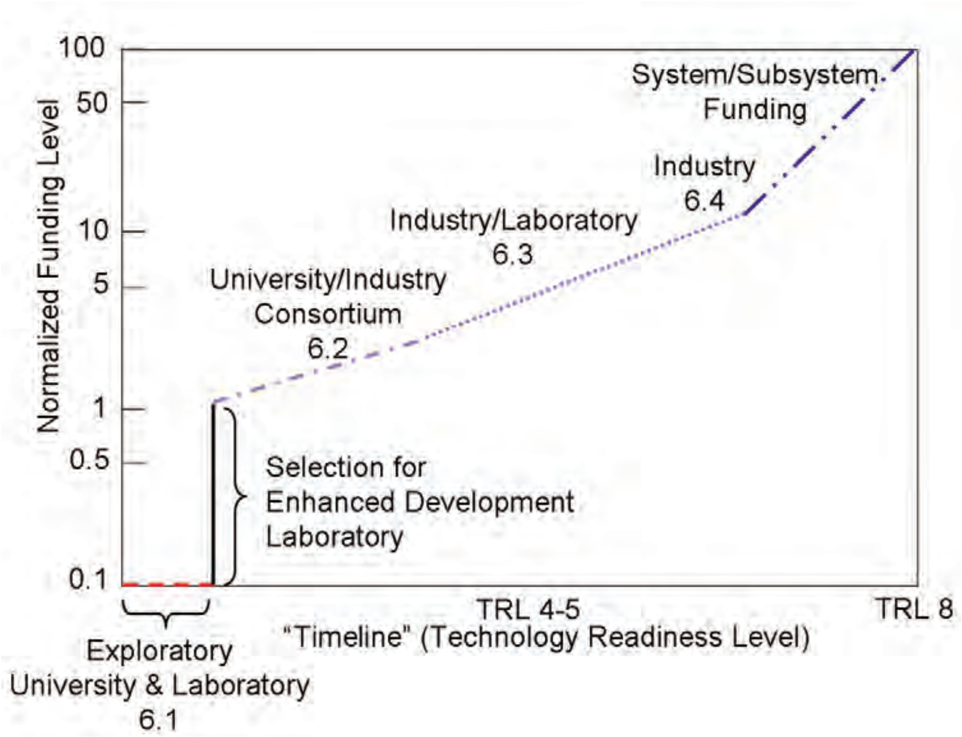

FIGURE 2.6 Notional funding profile for the eventual insertion of a new material.

TABLE 2.2 Typical Development Times for New Materials

Development Phase	Development Time
Modification of an existing material for a noncritical component	2 to 3 years
Modification of an existing material for a critical structural component	Up to 4 years
New material within a system for which there is experience	Up to 10 years. Includes time to define the material's composition and processing parameters.
New material class	20 to 30 years. Includes time to develop design practices that fully exploit the performance of the material and establish a viable industrial base (two or more sources and a viable cost).

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

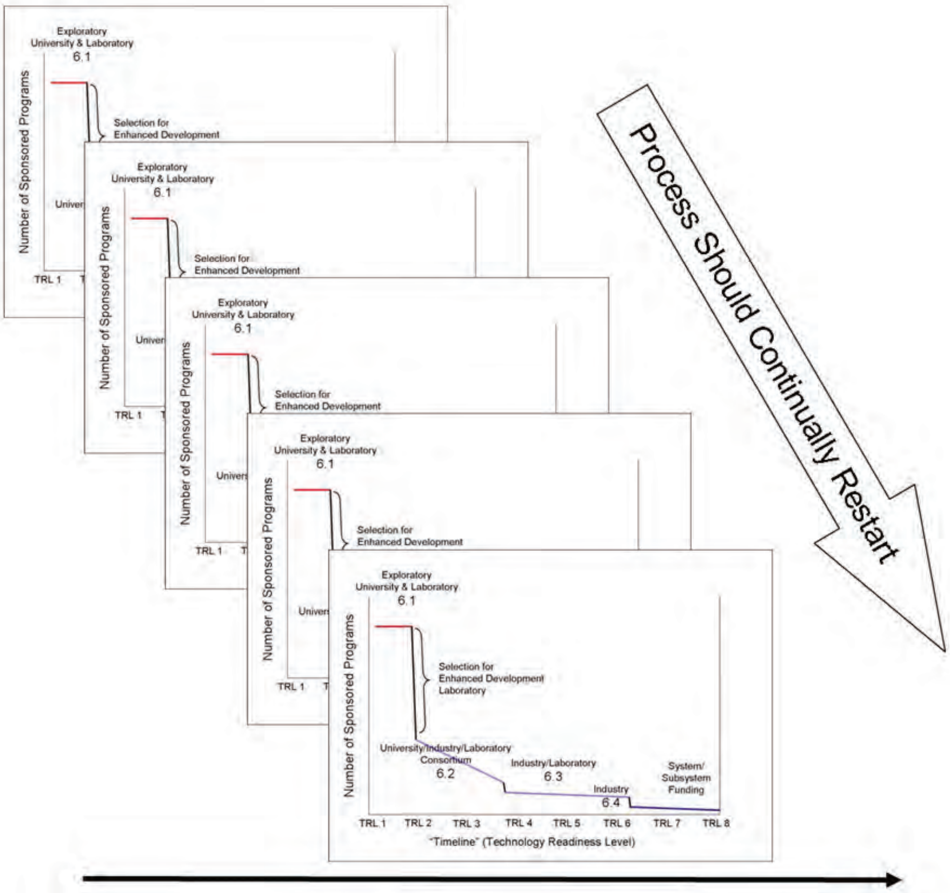

FIGURE 2.7 Ensuring a continuous flow of materials.

microstructure, properties, and processing routes. Whether through opportunistic or concerted efforts, new materials were developed to solve known problems, to expand a material's operational envelope, or even to enable new engine design concepts. Although all new M&P technology introduces some technical, budgetary, and scheduling risk to an engine program, those developments that represented revolutionary departures (i.e., the first application of a materials system or manufacturing process) have created the highest level of uncertainty. For these revolutionary materials, the materials developer too often struggles to anticipate reliably the potential for new-process-induced flaws, inherent materials defects, failure mechanisms, property balances, and manufacturing yield. An example of the struggles associated with such revolutionary developments is described in the case study in Section 2.5.1, below.

Early technical tools, team culture, and the management of M&P development were for decades relatively primitive compared to their counterparts today. Rather than following a formal structured process such as that described above, development was ad hoc, and it opportunistically exploited new ideas from universities (perhaps under 6.1 funding, as described in the notional process) but more often from promising M&P candidates derived from prior development programs and from innovation spawned and tested within independent research and development (IRAD) programs. Although cases may exist, it is worth noting that the committee was unable to find an example of a 6.1-funded material that could be tracked through continuous development to an engine insertion. Historically, materials research was usually performed by a team that included engine manufacturers, material-forging companies, and casting suppliers, all having well-staffed research departments and facilities and vibrant, ongoing research programs. Activities being carried out in universities under 6.1 funding were generally thought of as providing properly trained researchers for the workforce rather than providing the early development or discovery of candidates for continued maturation by the industry.

Regardless of the exact path, the fundamental development steps were the same as those of any other engineering discipline, then as now. These steps include the following (Figure 2.8):

- *Basic research and invention*—laboratory experimentation to explore and evaluate new materials and processing concepts;
- *Technical feasibility assessment*—subscale M&P implementation to refine the material architecture, evaluate processibility, and provide initial evaluation of material properties;
- *M&P demonstration*—full-scale M&P implementation to validate the process route, assess manufacturing issues, and generate design data curves; and
- *Production scale-up*—finalizing of manufacturing processes and making production-quality hardware for design data and material qualification engine testing.

Historically, the first two stages of development lacked formal guidelines and "tollgates" and instead depended largely on the experience, knowledge, and development style of the principal investigator. Prior to 1985 there were few computational tools except for chemical thermodynamics and PHACOMP methods (PHACOMP is a sigma phase prediction tool)[7] that the development team could apply to help guide development. Instead, development depended on an iterative,

[7] SUPER PHACOMP carries the NASA case number MFS-26164. It was originally released as part of the COSMIC collection. See http://www.openchannelfoundation.org/projects/SUPER_PHACOMP. Accessed May 3, 2009.

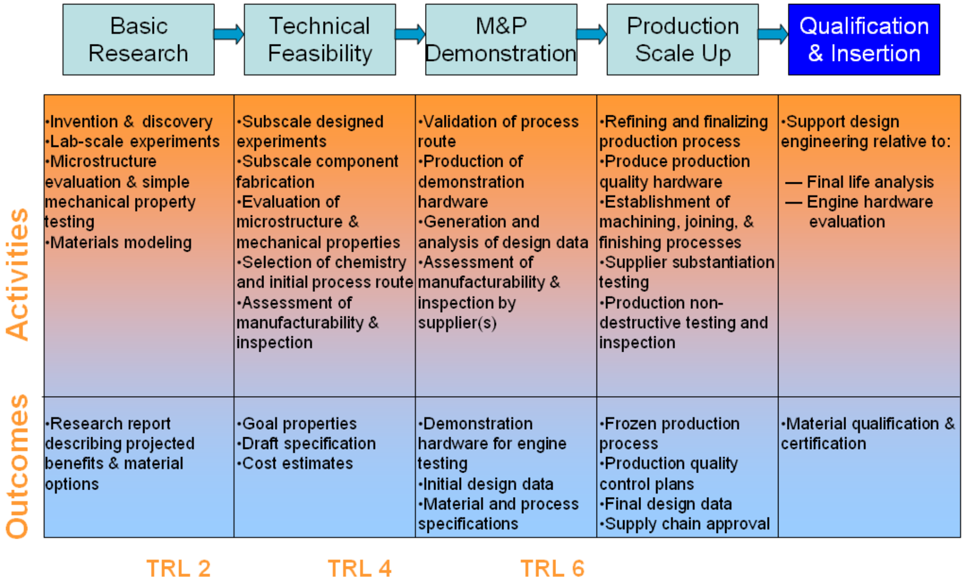

FIGURE 2.8 Description of the steps, activities, and outcomes in the materials development process. NOTE: M&P, materials and processes.

empirically driven, experimental plan which produced property data that distinguished success from failure.

The final development step (production scale-up) included material qualification, insertion, and support for fielded hardware. The qualification requirements for a material depended on both the material and the type of engine component targeted for insertion. Considerations in determining requirements included the impact of component failure on engine operation and flight safety, prior experience with the material in other components or engines, the prior history for similar materials and manufacturing processes, the quantity and quality of materials data, and the maturity of as-manufactured and in-service nondestructive inspection methods.

The committee notes that the TRLs listed along the bottom of Figure 2.8 indicate the approximate point in the materials development process where a TRL would fall, even though almost no TRL language was used in the development cycles in the early years. Because the materials development process steps remain essentially the same today, TRLs are included in Figure 2.8.

Early materials development, prior to the 1990s, was performed with only limited interaction with the other engineering disciplines. Following the receipt of materials requirements from the design engineering department, the materials department, in concert with suppliers, iteratively developed and characterized the

M&P and ultimately delivered specifications, drawing notes, and materials property design data curves to its engineering customer. During development, interactions among engineers across disciplines were limited, and confined to periodic reviews except when serious problems arose. In this climate, ineffective communication between disciplines and the absence of standard development processes too often caused a misunderstanding of materials requirements, misjudgment of insertion risks, and non-uniform development approaches, methods, and decision-making processes. In the early days, aerospace engine manufacturers developed and produced many capable engines, usually under the direction of highly experienced managers whose careers started in engineering and spanned the entire history of the evolving modern turbine engine.

The engine development cycle originally depended largely on component and engine testing to improve and validate engine designs, including constituent materials and processes. This make-or-break approach required a long (8 to 12 year) engine development cycle, involved a number of development engines and spin pit and component test rigs, and was costly; however, the cycle provided time for materials development and afforded ample opportunity for early materials evaluation during development-engine testing. For example, a designer could include a rainbow wheel of different turbine blade designs and materials in a test engine and assess their relative merits by evaluating features such as coating condition, tip erosion, leading-edge and tip cracks, and dovetail wear. The materials and engine development cycles were largely in sync unless either was delayed because of unexpected risks that had materialized. It should be noted, however, that development periods of approximately 10 years for materials mean that although the candidate materials were new to the engine being developed, they were materials for which there had been experience (see Table 2.1). According to Figure 2.8, this places the candidate materials at approximately TRL 4, which means that by whatever nonspecific route, the candidate materials had been developed to TRL 4.

Even with an 8- to 10-year horizon and some confidence that the materials choice at the start seemed promising, the level of insertion risk for any materials choice always increases during the course of a materials development program. For this reason, at the early stages, the development team had a number of materials and process options, but as development progressed, ultimately all but one option was discarded on the basis of the property data and processing findings generated during subscale trials. However, the subsequent materials processing scale-up, the generation of complete mechanical property design data curves, and the implementation of the full suite of component manufacturing operations too often uncovered materials issues and deficiencies that required further development. Coming late in the product development cycles, these surprises disrupted engine building and testing, caused engine design revisions, and required iterative processing trials that collectively affected both cost and schedule.

It is, of course, true that a prudent development plan requires that any new material must have a backup that keeps the engine design viable should the new material solution fail; however, if there was a completely acceptable, tried-and-true material backup available that had the same advantage as the new material and/or process offered, the backup would be the primary candidate. In the present climate, there are too few funds to develop the material and process for the primary new-material solution, let alone to carry along a backup.

2.5.1 Case Study: Powder Metallurgy "As-HIP" Superalloys

The following case study clearly changed the paradigm within the company involved for evaluation of the importance of considering risk in inserting new materials. This case and others like it throughout industry were studied by engine manufacturers and the government, leading to a new emphasis on risk aversion and the use of integrated product development teams (IPDTs).

The development of aerospace materials has offered up many lessons over the past 50 years, and all too often these lessons have come the hard way—particularly those associated with the development of revolutionary materials. Whether they break new ground in composition or in processing, revolutionary materials usually promise significant advancement in materials capability and engine performance. But such materials also pose higher risks and often present processing and manufacturing-infrastructure challenges. This case study recounts the development of powder metallurgy (PM) turbine components consolidated using hot isostatic pressing (HIP).

In the 1960s, the advance of turbine technology encountered what seemed to be a materials roadblock. Turbine designers wanted higher-temperature and stronger superalloys to increase turbine temperature and rotational speed, reduce the number of turbine stages, and thereby gain improved turbine efficiency and performance. But stronger, more highly alloyed superalloys exhibited excessive ingot segregation and both poor hot workability and cracking when manufactured using conventional cast and wrought processes (Figure 2.9).

In 1968, materials engineers at Federal Mogul and Pratt and Whitney demonstrated that powdered metal superalloy processing was viable and that it could achieve mechanical properties equivalent to those of traditional cast and wrought materials.[8,9] The main idea behind this advance was sound—the atomization of a

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[8] National Research Council. 1986. "PM Superalloys—A Troubled Adolescent" (R.L. Dreshfield and H.R. Gray) in *Net Shape Technology in Aerospace Structures, Vol. III. Appendix: Emerging Net Shape Technologies.* Washington, D.C.: National Academy Press.

[9] J. Smythe. 2008. "Superalloy Powders: An Amazing History," *Advanced Materials & Processes* 166(11):52-55.

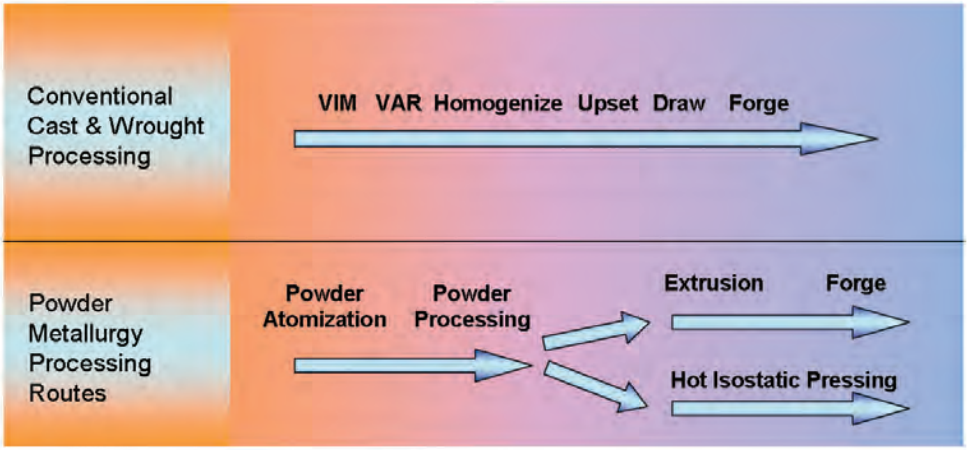

FIGURE 2.9 Comparison of typical steps used for conventional cast and wrought processing and powder metallurgy processing of aerospace superalloys. NOTE: Acronyms are defined in Appendix F.

superalloy melt produces a fine, rapidly solidified powder, having less elemental segregation. But developers needed to find a consolidation process that produced the best combination of materials properties and manufacturing cost. Initial candidates included HIP consolidation either followed by forging, extrusion, and more forging, or used directly from HIP consolidation, so-called as-HIP, to directly produce a shaped compact (see Figure 2.9). The latter option, as-HIP, promised the added cost benefits of streamlined consolidation and near-net-shape compacts that required less machining; for these reasons it was selected by several engine programs for production rotor hardware. In retrospect, the expectations of improved mechanical properties and significant manufacturing cost savings may have overshadowed the perception of risks associated with the product introduction of nonforged rotor as-HIP components made by a nascent PM manufacturing base. Were as-HIP promises too good to be true?

Unlike cast and wrought processing of highly alloyed superalloy compositions (such as Rene '95), early as-HIP development yielded fully dense, crack-free component pre-forms that exhibited good mechanical properties. The superalloy powder for these as-HIP, near-net-shape compacts was produced using laboratory-scale gas-atomization equipment operated by highly skilled research technicians. However, as production rates ramped up, production equipment scaled up and relocated to the factory floor, and the low cycle fatigue (LCF) test database grew in size, engineers became concerned about the cleanliness of the as-HIP product. They observed that the lives of LCF test bars were controlled by anomalous defects of four types: voids, discrete chunky ceramics, ceramic agglomerates, and reactive agglomerates that decorated prior powder-particle boundaries (PPBs).[10] More troubling, the population of LCF test-bar lives was bimodal, with a significant short-life subpopulation composed of test bars for which LCF failure initiated at larger defects, usually located at or near the surface of the test bar. Moreover, materials engineers found that although the size of most defects was limited by the powder screen size, PPB defects were considerably larger. These engineers postulated and then demonstrated that PPB defects originated from reactive exogenous material (e.g., rubber, iron oxides, and vacuum grease) that had contaminated the powder prior to HIP thermal processing.[11] Upon HIP processing, reactive contaminants decomposed, generating gaseous products that decorated the surrounding powder surfaces and reduced interparticle strength upon compaction.

Concerned but not deterred, engine manufacturers and supplier engineers undertook process-improvement programs and instituted additional quality controls. Recognizing that the size of melt-related oxides and those reactive contaminants that were introduced prior to powder screening were related to screen size, powder was screened to a finer, 150 mesh size. Also, engineers scoured powder production and handling facilities in order to identify and then remove sources of reactive contaminants. Numerous sources were identified, such as elastomer O rings in gas-line valves and fittings, gaskets, oxides from weld debris inside powder transfer lines and storage containers, fibers from wipes used to clean handling equipment, and particulate matter distributed by means of factory air-handling equipment. Even as improvements were made to address these problems, other efforts involved introducing strict cleaning protocols, implementing clean-room facilities, and heating powder to volatilize organic contaminants.[12]

Quality control (QC) enhancements were no less scrupulous. Powder lots were tested using water elutriation to gauge cleanliness, large-bar LCF testing was added as a QC requirement for powder-blend qualification, and "HIP'ed" compacts were inspected using high-resolution ultrasonic methods. Meanwhile, materials and design engineers were busy assessing the impact of cleanliness on the cyclic life of PM rotor hardware. The bimodal life distribution of LCF bars introduced new challenges in defining statistically valid minimum LCF curves, and the defect sensitivity of PM superalloy elevated the importance of fatigue-crack growth testing and the statistical determination of defect size distributions. Design engineers concurrently developed probabilistic lifing methods based on fracture mechanics to complement classical LCF life-prediction methods. Also, extensive spin pit testing was carried

[10] D.R. Chang, D.D. Krueger, and R.A. Sprague. 1984. "Superalloy Powder Processing, Properties, and Turbine Disk Applications," Superalloys 1984, Conference Proceedings, AIME, pp. 247-276.

[11] D.R. Chang, D.D. Krueger, and R.A. Sprague 1984. "Superalloy Powder Processing, Properties, and Turbine Disk Applications," Superalloys 1984, Conference Proceedings, AIME, pp. 247-276.

[12] D.G. Backman and J.C. Williams. 1992. "Advanced Materials for Aircraft Engine Applications," *Science* 255(5048):1082-1087.

out to validate component lifing methods and to assess the volumetric scaling of associated defect distributions.

By the late 1970s, suppliers and engine-manufacturer engineers had been fully exposed to the technical risks of as-HIP superalloy technology and the challenges of concurrently building powder metallurgy manufacturing capability while production was underway. Through painstaking efforts, suppliers had improved powder cleanliness and engine-manufacturer engineers had learned to manage the quality and life of as-HIP components. Meanwhile, the cost of as-HIP products soared because of extensive quality testing, more tightly controlled processing, and the lower yield of 150 mesh powder. But a most important question remained unanswered: Could an engine manufacturer successfully manage the risk of powder cleanliness—particularly the risks associated with reactive PPB defects?

In 1980, an F-18 aircraft, powered by two GE404 engines, crashed at Farnborough, United Kingdom; the crash was attributed to the failure of an as-HIP Rene '95 low-pressure turbine disk.[13] Although the cause of failure could not be determined because critical disk fragments were never recovered, clearly the disk failure and resulting F-18 crash heightened the perceived risk of as-HIP superalloy cleanliness and defect intolerance, and so began the end of the as-HIP superalloy processing. The final abandonment of as-HIP prompted the urgent development of several alternative superalloy technologies as replacements.

This case study of the abandonment of as-HIP superalloy technology provides an opportunity to learn several lessons. Foremost, *an underestimation of the risks associated with the insertion of not-well-understood materials processed in novel ways can have catastrophic consequences.* The potential problems created by what is not known can easily outweigh the confidence that one gains from what is known. The harmful consequences following the events recounted above included design and manufacturing disruption, urgent activity to develop replacement technologies, and the emergence of distrust of the traditional materials development process. Indeed, in the aftermath of this accident, the development of alloys, such as Rene '88 damage tolerant and direct age IN718, as well as the application of isothermal forging as the preferred PM processing route for PM disk materials, proved to eliminate the as-HIP problem and also dvanced turbine materials technology significantly. But *unfulfilled material promises, such as that described in this case study, also taught a generation of young design engineers and managers to avoid new materials technology lest they be ambushed by similar problems with the next new material.*

The longer-range consequences for future propulsion materials are clouded by the competitive fallout of the 1980s engine wars, the 1990s economic downturn in the propulsion business, and the resulting reduction of the overall aerospace engineering workforce. These latter years saw lower aerospace materials development,

[13] For further information, see http://ammtiac.alionscience.com/about/. Accessed August 11, 2009.

lower governmental and industrial investment in structural materials, and a waning interest in aerospace careers by materials engineering university graduates. Shortcomings such as those demonstrated by this case study probably also contributed to the institution of risk-abatement efforts such as those represented by formal engine development processes and the institution of TRLs. These methodologies require a level of proof for all new technologies before engineers can commit the technologies to the start of production.

2.5.2 Simultaneous Development

Up to this point in Chapter 2, materials development has been presented as a progression toward increasing materials maturity and a concomitant decrease in insertion risk (i.e., increasing TRL). This progression is the basis of the notional development process represented in Figures 2.5 through 2.7. This progression toward maturity is also evident in the Air Force's S&T program (Figure 2.10). The basic research (6.1), applied research (6.2), and advanced technology development (6.3) elements discussed above constitute the Air Force's S&T program. Also shown is "6.3 Manufacturing Technology," which represents the Air Force's ManTech Program. Unless the engine developments are for demonstration engines

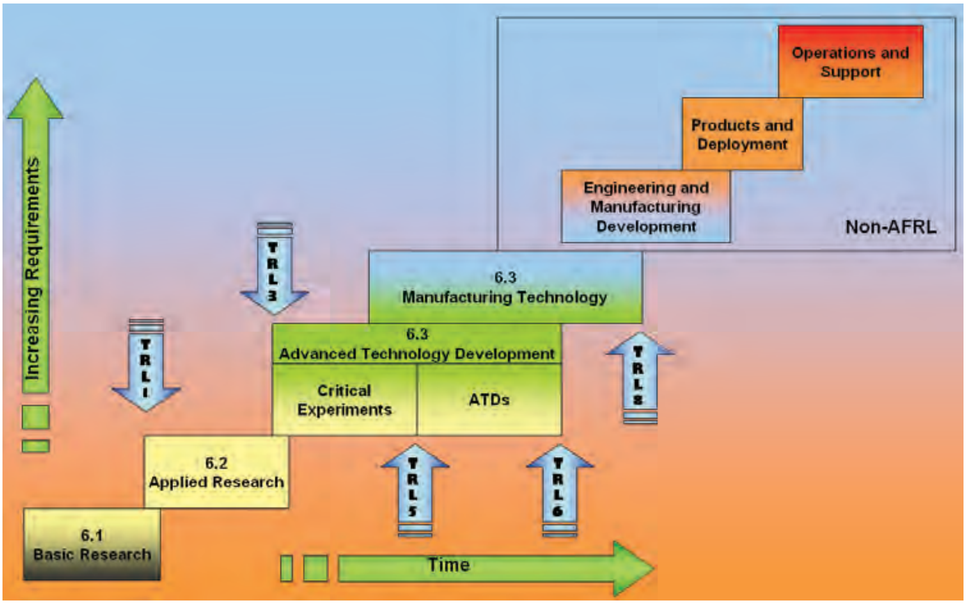

FIGURE 2.10 The science and technology program of the U.S. Air Force. NOTE: Acronyms are defined in Appendix F.

as in the Integrated High Performance Turbine Engine Technology (IHPTET) Program discussed below, the program elements in the non-AFRL portion of Figure 2.10 are the Air Force's Acquisition Program, managed by the system program offices. Also shown in Figure 2.10 are the TRLs expected at the successful completion of the work in the various stages.

This development process, as discussed below in Section 2.6, forms the basis for the Air Force's research and development program. On paper it seems to present a logical framework, and it illustrates the various elements of the S&T program and their relationships to the system customer (program elements in the non-AFRL portion of Figure 2.10) and the various TRLs for each stage. But in the case study described in Section 2.5.1, development did not follow the model path shown in Figure 2.10, in which a new composition or process transitions sequentially from one totally isolated or independent element to another. As suggested in the case study, this progression in maturity is not successive with time. In fact, there is no formal transition or handoff from basic research to applied research, as discussed in the notional process, and then on to system development and then to ManTech.

For a new material, the S&T and ManTech elements might be operating simultaneously, with multiple programs in each. As shown in the case study in Section 2.5.1, *as the maturity level of M&P increases, and even into production, work at lower TRLs may be necessary to address an unforeseen issue.* This cyclical nature of materials transition is not unusual and in many cases is a known element of risk for high-performance applications.

A well-known nonpropulsion materials technology maturation that made intentional use of this "simultaneous process" is the development of advanced composites. Early work showed that significant weight savings, fatigue resistance, and corrosion resistance were possible with advanced composites (i.e., laminated anisotropic fiber-reinforced materials containing high-strength and high-stiffness fibers in a polymer matrix, which was a new technology at the time). Included in this class of materials were both thermoset and thermoplastic matrix materials, and carbon/graphite, boron, aramid, and E-glass fibers. To take advantage of what this class of materials had to offer in as short a time as possible, programs in each of the program elements shown in Figure 2.10 were underway at the same time (ca. the late 1960s, 1970s, and early 1980s): 6.1 programs in mechanics, 6.2 programs in materials and process development, and 6.3 programs in design and data; ManTech programs for producibility; and industry IRAD (not shown in Figure 2.10). In addition, there were near-term application opportunities such as the F-15, F-16, B-1, F-18, F-117, B-2, and others. While each program element shown in Figure 2.10 could benefit from efforts made in the others, the unique focus of each gave these programs a level of independence that allowed them to run simultaneously and still be very effective. The 6.1 mechanics programs were not focused on a specific material but rather on the overall class of materials. The 6.3 programs were materials-specific and as such relied on the 6.2 work and/or industry efforts to provide the materials. The 6.2 work on improved materials, processes, and tools relied on government and industry efforts for new approaches as well as for the transition of the new technology.

The overall "class of materials effort," with "specific materials efforts," allowed fundamental tools, new M&P data, and producibility to be worked on at the same time. This simultaneous process proved to be quite effective in reducing risk and achieving timely transitions.

2.6 THE EVOLVING MATERIALS DEVELOPMENT PROCESS

Although the traditional steps undertaken during M&P development are still used today, the landscape in which materials developers' work has undergone significant changes. Some of these changes, which include technical, programmatic, and cultural elements, have increasingly challenged the M&P development process, have increased the risk associated with materials insertion, and have even led some engine designers and now even government-sponsored demonstration-engine programs to de-emphasize the deployment of new materials. Other changes have aided the materials and engine developers.

In this changing environment, the cycle time gap between the product and materials development represents the largest challenge to materials development and insertion. Figure 2.11 shows the relationship between materials and engine

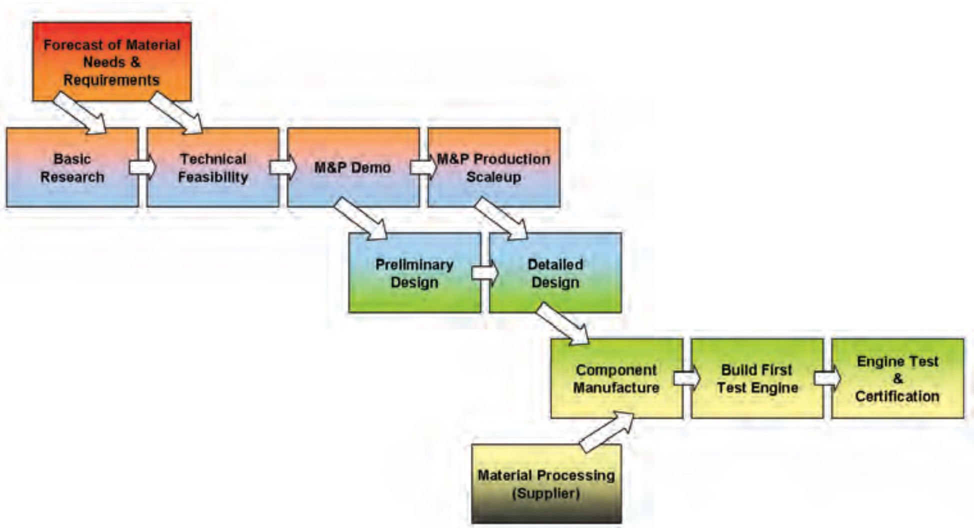

FIGURE 2.11 Relationship and conceptual timeline between materials engineering, engine design, and manufacturing activities during component development. NOTE: M&P, materials and processes.

development. Since the mid-1980s, the emergence and evolution of computer codes for design analysis have allowed the design engineer to use computation to eliminate a significant number of engine and component tests. Also, the application of structured engine development processes, integrated product development teams, and computer-based optimization have reduced the number of engine design iterations, further expediting the engine development cycle and in the process widening the cycle gap between the materials development cycle and the engine-development cycle.

Although engineers benefit from IPDTs and structured materials development processes, materials development activities remain highly dependent on costly and time-consuming experiments, processing trials, and mechanical property testing. Some modest gains in cycle times have been achieved, but the cycle time gap is now measured in many years. For example, the development of a new material can take as long as 20 years depending on the material of the targeted material class (see Table 2.1). In contrast, engine development can now take as little as 2 years for a derivative engine and perhaps 6 to 8 years for an engine based on an all new turbine core.

Also, materials development differs from the design activities during engine development in several important ways. While both demand creativity, the development of a new material is more dependent on the vagaries of invention and discovery and is confounded by a plethora of materials science and processing mechanisms that often compete, are nonlinear, and are difficult to describe or predict mathematically. Simply stated, there is a fundamental knowledge and technology gap separating the mechanical and materials engineering disciplines. This gap has exacerbated the associated development-cycle time gap and produces technical and programmatic risks that together create uncertainty and impede the development and insertion of new materials.

Resolution of the development-cycle gap is confounded by a number of other changes that have taken place within the propulsion community, including reduced investment in new M&P and increased reliance on emerging materials systems for future propulsion gains. Historically, the dominant approach used by engine manufactures to ensure a reliable stream of new materials has been to maintain active internal materials research in strategic areas and leverage research undertaken by universities, national laboratories, and throughout the materials supplier base. Prior to the 1990s, there was a vibrant climate for such research, but more recently much supplier-based development has been sharply curtailed, internal engine-manufacturer materials research funding has been reduced and earmarked to address nearer-term needs, and fewer university researchers are dedicated to structural materials. Therefore, in contrast to earlier times, there are now fewer materials choices, and less technical information is available on which to base materials development decisions.

Also, some materials engineers believe that the capability of workhorse superalloy and titanium alloys is nearing exhaustion and that further evolutionary change in their chemistry and processing is likely to yield only modest advances. In the absence of computational tools to identify superior alloy compositional spaces more effectively, these skeptics are likely correct. But in the meantime, the drive to improve engine performance (higher temperatures and light weight) has rightly focused more materials research and development on intermetallics and composites such as the ceramic SiC-reinforced SiC system. But, these alternative materials systems may actually increase the development-cycle gap and pose additional schedule and insertion risks associated with the immaturity of the supplier base and uncertainties associated with materials defects, manufacturing flaws, and limited knowledge of failure modes and other durability issues for these newer, less-mature classes of materials.

Conversely, materials development has also been aided by several changes in the propulsion engineering culture, including the adoption of IPDTs and the establishment of formal product development cycles and TRLs. Also, the long-standing traditional, ad hoc materials development approach could not be effectively sustained as the aerospace propulsion industry matured, engine products proliferated, and competition, both domestic and global, intensified. Consequently, aerospace engine manufacturers began to introduce structure and discipline into development methodologies, including those used to establish new materials. Each engine manufacturer took different routes, but they typically included methods such as continuous improvement, concurrent engineering by IPDTs, and formal product (and materials) development. This approach has also been adopted by the government in awarding new development and demonstration contracts.

The implementation of IPDTs created cross-disciplinary teams armed with team methods and decision-making tools for increasing the immediacy and effectiveness of communications, the consideration of competing viewpoints, and decisions that integrate knowledge from the full spectrum of stakeholders. Some engine manufacturers even embedded IPDT concepts through organizational structures that enhanced their execution, such as with centers of excellence. The institution of formal product- and materials-development processes further enhance materials development by imposing structured processes to ensure that standardized best-development methods are uniformly applied across an organization. These processes typically include development steps that list and describe required development activities, engineering methods, risk analyses, and best practices that must be systematically followed during the development of a new material or product. A management team usually oversees the IPDT executing the development and ensures that the process is followed and that required efforts at tollgates are accomplished prior to a transition to the following development stage. These tollgates typically either closely follow or duplicate the government-developed TRLs and milestones that define the interim technical requirements and preconditions necessary for advancing to the subsequent product development stage.

In the end, the cycle gap in materials development and engine development and the increasing emphasis on risk aversion imposed by TRL and milestone tollgates have led to the near disappearance of introducing revolutionary new materials into new engine development. This cycle gap and the lack of funding prior to the demonstration-engine level are the basis for the reference above to the valley of death (Section 2.2.4). In turn, this de-emphasis on introducing new materials has led to fewer job openings for materials people in engine manufacturing and supplier-based jobs and a general dismantling of facilities. These developments have also had an effect on materials programs at U.S. universities.

2.7 THE ROLE OF LARGE PROGRAMS IN THE DEVELOPMENT OF MATERIALS AND PROCESSES

The evolving nature of the materials development process described in Section 2.6 has had a dramatic effect on the funding of materials development within new engine development programs. This evolving effect can be seen by examining programmatic objectives that at first did not take into account the consequences of design-cycle accelerations, of risk aversion, and of the use of IPDTs with respect to the eventual de-emphasis on introducing new materials and processes into demonstration programs. Since about 1986, there has been a change in the amount and purpose of funding above the 6.3 level made available within the DOD for R&D in materials and processes for demonstration engines. After that date many of the types and purposes of materials development became tied to specific programs. This "directed funding" led large amounts of productive activity to move materials to higher TRLs. Major programs that became the drivers were as follows: National Aerospace Plane–Materials and Structures Augmentation Program (NASP-MASAP), High Speed Civil Transport–Enabling Propulsion Materials (HSCT-EPM) Program, Integrated High Performance Turbine Engine Technology (IHPTET), Integrated High Payoff Rocket Propulsion Technology (IHPRPT), and Versatile Affordable Advanced Turbine Engine Program. These programs provided the rationale and focus for new materials, defined the goals that had to be met, and often provided the opportunity to demonstrate new materials in a relevant environment (TRL 6). But the reduced funding in these demonstration programs and the adaptation of the resulting fewer engines and risk aversion have led to much smaller amounts of available funds for the transitioning of materials up the TRL ladder.

2.7.1 Major Program Pushes in Materials

The following section describes some of the major program efforts that have been made in materials.[14]

National Aerospace Plane—Materials and Structures Augmentation Program, 1988-1991

The goal of the National Aerospace Plane Program was to develop an experimental aircraft, the X-30, to explore the entire hypersonic-velocity flight range. Other objectives included the support of future national security, civil applications, and a reduction in the costs of space launch. According to the NASP mission statement quoted by President Ronald Reagan in his 1986 State of the Union address, NASP would "by the end of the next decade, take off from Dulles Airport and accelerate up to 25 times the speed of sound, attaining low earth orbit or flying to Tokyo within 2 hours."[15] Given the demanding conditions of flying a vehicle from a horizontal take-off to Mach 25 and using hydrogen as the fuel, materials were identified by the Defense Science Board as one of six critical technologies.

The Materials and Structures Augmentation Program under NASP was a 46-month effort begun in March 1988. It was funded at $136 million through the NASP Joint Program Office (JPO). A materials consortium was formed and managed by the NASP JPO and an industry executive steering committee. Companies also shared both completed and current industry research and development (IR&D) on a voluntary basis. The consortium focused on developing producible processes for a range of relevant materials (see list below). The development of an advanced supplier base was a critical part of the program, as the team focused on establishing materials and structural designs that met the requirements of the vehicle and the mission. The program was canceled before a demonstration vehicle was built, but the stable funding over 4 years, albeit abruptly ended, enabled significant advances in many materials classes that were to a lesser extent picked up by other programs and other means. Relevant materials advances from the NASP Program are listed below:

- Titanium aluminide development and processing,
- Titanium matrix composites,
- Carbon-carbon,
- Coatings for refractory alloys, and
- High-conductivity materials.

[14] The information in Section 2.7.1 was provided to the committee by Charles Ward, Air Force Research Laboratory, May 2009.

[15] Ronald Reagan, 1986 State of the Union address.

High Speed Civil Transport—Enabling Propulsion Materials Program, 1990-1999

The High Speed Civil Transport was going to be a next-generation supersonic passenger jet, flying 300 passengers at greater-than-Mach-2 speeds at a ticket price of no more than comparable, slower flights. The program was initiated in 1990 and terminated in 1999. Again, materials were acknowledged to be critical for the success of the program, and the Enabling Propulsion Materials Program was created and funded at $40 million to $45 million per year (total: $280 million to $315 million). This stable and significant level of funding over approximately 9 years resulted in very significant advances over a broad range of materials classes, as seen in the following list:

- Superalloy disk materials—ME-3, ME-16, and LSHR;
- Thermal barrier coatings (TBCs), especially low thermal conductivity TBCs;
- Single-crystal blade alloy—EPM 102 (MX4, PW1497);
- Gamma TiAl, particularly casting process development;
- Ceramic metal composites for combustor liners—SiC/SiC;
- Environmental barrier coatings for Si-based ceramics; and
- Dual microstructure/property heat treatment for disks.

It should be noted that the HSCT-EPM Program began in the early stages of the transition in the materials development process and was associated with a development program that was expected to take a decade or more. Depending on the level of readiness, such a long development horizon assumed that the material and demonstrator cycle times would not be far out of sync.

NASA Transitions

NASA does not classify its programs using the terminology employed by the DOD (i.e., 6.1, 6.2, 6.3, and so on), but its effort appears to have been primarily 6.2 in nature. Both the NASP-MASAP and the HSCT-EPM Programs were very important in pulling materials technology forward to meet the very demanding goals of high-speed flight. But neither program was associated with an engine or a vehicle demonstration effort, so that insertion of the materials that were developed into actual systems had to await the formulation of new programs, military or commercial, that needed new materials capability. This lack of demonstrator engines hampered transitions of these materials out of the 6.2 level, but at least it moved select materials upward on the TRL ladder; this was particularly important to the IHPTET Program, discussed below.

A number of the materials technologies that were investigated in the NASA programs are now in service, but they have required significant additional investment to bring them to fruition—that is, other programs picked up where the NASA program left off with at least a promise that investments in moving things farther up the TRL ladder would lead to a payoff in terms of a higher probability of insertion. For example, gamma TiAl is scheduled to be used by General Electric as low-pressure turbine blades on its GEnx (GE next-generation) engine, which will power the Boeing 787 and Boeing 747-8 aircraft. This is the first large-scale use of this material on a commercial jet engine; it has not yet been designed into a military engine. Similarly, the new superalloy disk materials, ME-3 and ME-16, are only now finding their way into newly designed engines.

Integrated High Performance Turbine Engine Technology Program, 1988-2005

The IHPTET Program began in 1988 and was driven by phased goals related to the performance of gas turbine engines, the ultimate goal being a doubling of the performance (thrust to weight) for military engines. The program was built around a series of time-phased engine demonstrators that allowed for the timely insertion of technology. The program was jointly funded by the DOD and industry, with the total government expenditure being $2.2 billion (total program funding, not including materials). The materials effort was funded separately, with the Air Force materials budget contributing approximately $6 million per year and the Navy materials budget approximately $4 million per year. Again, the IHPTET Program was begun in the early stages of the changes in engine-design paradigm shifts and materials cycles were started early in the program, rightly assuming that their cycle development would be in sync with the demonstrators developed in the program. Materials development was acknowledged as an enabling technology to meet the objectives of the program. Because of the importance placed on materials in the program, the sharing of pre-competitive knowledge was part of the early stages of the program; it allowed for the sharing of materials information that might have come from IR&D-funded projects, which placed materials at higher-than-6.1 levels at the beginning of their consideration under the IHPTET umbrella.

The IHPTET Program also provided the rationale for new materials—recall comments at the beginning of Section 2.5 indicating that materials and process developments were driven to solve known problems, to expand a material's operational envelope, or even to enable new-engine design concepts. As such, the IHPTET Program set the goals that new materials had to meet and, importantly, provided the opportunity to demonstrate new materials in a relevant environment (TRL 6). More than 40 demonstrator engine tests were conducted over the full length of the IHPTET Program. These demonstration opportunities inherent in the IHPTET Program cannot be overemphasized. While both the NASP-MASAP and the HSCT-EPM Programs were very important in pulling materials technology forward to meet the very demanding goals of high-speed flight, neither program was associated with an engine or a vehicle demonstration effort. The insertion of the materials that were developed into actual systems had to await the formulation of new programs, military or commercial, that needed the capabilities inherent in the new materials. By contrast, the insertion of technologies developed under the IHPTET Program can be readily traced to their successful demonstration. Following are materials advances from the IHPTET Program:

- Advances in wrought gamma TiAl alloys,
- Advances in SiC/SiC composites,
- High cycle fatigue of titanium, and
- Organic matrix composites.

Integrated High Payoff Rocket Propulsion Technology Program, 1995-Present

The Integrated High Payoff Rocket Propulsion Technology Program, which began in 1995, is a collaborative effort initiated by the DOD, NASA, and industry. The primary objective of IHPRPT is to double rocket propulsion capability by 2010. Because materials were recognized as critical to the success of the technology goals, an IHPRPT Materials Working Group (IMWG) was chartered by the IHPRPT Steering Committee in February 1997. The IMWG is composed of representatives from various NASA, DOD, and industry organizations. AFRL's Materials and Manufacturing Directorate first received funding for participation in the IHPRPT Program in 2001 and began conducting research and development efforts designed to address specific material and component concerns. Unlike the funding for the IHPTET Program, the funding for the IHPRPT Program has not been straightforward and has been somewhat disconnected from the program, leading to an unstable funding environment for materials research.

Versatile Affordable Advanced Turbine Engine Program, 2005-2017

The ongoing VAATE Program is the follow-on program to IHPTET; the program appears similar to the IHPTET Program in that it has very concrete goals, both technology goals and cost goals. But from a materials point of view, the resemblance is superficial. VAATE is a capability-based program; engine goals are subservient to system and platform goals. Improved engine performance is important but is no longer the major selling point of the program. In the present environment, fuel efficiency, not performance, is the main driver behind the current program centerpiece: the Advanced Versatile Engine Technology (ADVENT) demonstrator engine. It should be noted that some of the materials development efforts left over from the IHPTET Program due to the cancellation of IHPTET Phase III were picked up by VAATE. These included, for example, the upcoming demonstration of the second vane row in the high-pressure turbine of the F-136 engine core, a joint program between Rolls-Royce and General Electric, which is sponsored under the VAATE umbrella. Other materials insertions planned for IHPTET Phase III were considered too high risk to be undertaken in VAATE, however. Also, some materials insertions through the VAATE Army Turboshaft Program continue; however, these do not constitute new materials work but rather engineering and process efforts aimed at continuing some of the insertion plans left over from the cancellation of IHPTET Phase III.

Another major difference between the IHPTET and VAATE Programs is the much smaller number of demonstrators that are currently planned during the VAATE Program. This means that the transition of materials into engines will be highly constrained by the timetable of the few available demonstrator engines. This situation has already impacted the planned materials development programs: to ensure transition, the planned Air Force materials programs have become highly focused. Their timing is critical: any schedule delays may mean that these programs will be irrelevant to the VAATE Program. Since VAATE is an ongoing program, more specifics will be covered in the Chapter 3, which deals with the present materials-development environment.

2.7.2 Discussion

It is clear that national programs prior to the VAATE Program provided not only incentive and direction but also periods of robust and stable funding for materials and processes research and development. In addition, the IHPTET Program in particular provided demonstrator engines that were specifically identified as placeholders for demonstrating new materials. Although those materials were not part of the IHPTET Program funding directly, IHPTET's expecting new materials to transition into IHPTET and setting the requirements for these developments led to concomitant funding from DOD materials programs to be transitioned into the demonstrator engines, and this in turn furnished a rationale for continuing the materials program funding. The importance of the availability of engines to test new materials cannot be overstated. In VAATE—the program that replaced IHPTET—materials development, although stated as one of its goals, does not have a separately funded materials and processes funded line. Not only are there fewer demonstrator engines and thus few transition opportunities, but the availability of these demonstrators for use as new materials demonstrators is also at present unfunded; currently these demonstrators appear in the program milestone charts as unfunded placeholders. What is clear is that VAATE has no specific performance objectives that require new materials. In the VAATE Program, even though it is an engine-demonstrator program, the new paradigm of risk aversion and IPDTs has come to full maturity.

This situation presents a quandary regarding where the incentive to develop new materials for propulsion lies within the Air Force Research Laboratory. The role of Focused Long Term Challenges (FLTCs) is discussed in Chapter 3; briefly, FLTCs enable the AFRL to describe future capabilities and help develop a technological path that can shape the future Air Force. The FLTC process provides the planning construct to define future priorities by describing the problems needing to be addressed as opposed to the specific technology solutions to be pursued. However, in terms of the development of new materials for propulsion, the FLTCs give little support for the level of materials development funding at the 6.3 level and beyond that was present under the IHPTET Program. Without the pull for new materials provided in new development engines from the AFRL's Propulsion and Power Directorate and acquisition and program offices, there exists little support for the infusion of funds into new materials for propulsion within the AFRL's Materials and Manufacturing Directorate. Given the competing materials interests within the Materials and Manufacturing Directorate, it is inevitable that funds for structural materials development for propulsion applications will languish. IHPTET itself did not stand alone, having depended on the availability of materials brought to high 6.2 levels from other national programs such as the NASA HSCT-EPM Program. At present there are essentially no engine-specific structural material programs being funded in or outside the DOD targeted on advancing 6.1 materials to high 6.2 level.

2.8 COMMON THEMES FOR SUCCESSFUL MATERIALS DEVELOPMENT

The successful development of any technology requires a number of events or factors plus the long-term involvement of management, researchers, and users. The role of the visionary that will continually champion the progression of the material up the TRL ladder is especially important, as technology needs change, applications and partners disappear and appear, and funding stops and starts. The development of new or advanced materials currently requires extensive amounts of time and money. It is critical to implement approaches to make the development more efficient.

2.8.1 AFRL's Identification of Important Elements

Listed below are what the AFRL considers to be the three major elements for success in a materials technology program.[16] This list is then expanded with elements from other sources, but it is clear that AFRL's list is based on its belief that a successful materials program must be associated with a concomitant engine- or aircraft-development program. In other words, the AFRL mind-set appears to be

[16] Presentation to the committee by C. Ward and D. Hardwick, AFRL, July 20, 2009.

that a materials development program cannot be successful without the pull of a new engine- or aircraft-development program. Thus, its three major elements for success start with the umbrella engine/aircraft development program.

- The engine/aircraft development program itself must be well defined and must have specific end-point objectives, which are clearly articulated in the program's mission statement.
- Concomitant with a clear mission statement is a clear acknowledgment of the need for material advances in order to fulfill the goals of the program.
- A sufficiently funded companion materials development program is tied to the goals of the overall engine/aircraft development program—that is, a commitment to fund materials development is part of the larger technology development program.

In their discussion of these elements of success before the committee, AFRL staff members[17] gave as an example of a successful materials-advancing program the 1988-1991 National Aerospace Plane Program. They cited each of the major elements listed above and repeated here:

- *NASP mission statement*—"By the end of the next decade, take off from Dulles Airport and accelerate up to 25 times the speed of sound, attaining low earth orbit or flying to Tokyo within 2 hours."
- *Acknowledgment of materials need*—The Defense Science Board identified materials as one of six critical technologies for system development of the national aerospace plane.
- *Commitment of funding*—The NASP Materials and Structures Augmentation Program, with stable funding of approximately $125 million, was created.

Although many believed that the NASP Program was unsuccessful in that it was ended abruptly without meeting its goals, the presenters pointed to the fact that NASP's companion materials development program, MASAP, was successful in advancing the state of the art of propulsion materials. In Section 2.7.1, see the discussion of the NASP Program and in particular the materials advances made in the MASAP and used by the propulsion materials community as the basis for further developments. It should be noted that AFRL's list of the three elements of a successful materials maturation requires that materials candidates be available at high 6.2 levels.

[17] Presentation to the committee by C. Ward and D. Hardwick, AFRL, July 20, 2009.

2.8.2 Other Common Themes of Successful Materials Developments

It is clear that AFRL's focus in identifying its three elements of success is tied to major pulls in either system developments or demonstrator engines. But as indicated in tracing the history of various large programs, it is clear that the environment has changed. The present mind-set holding that new engines are not needed because new major systems are not on the horizon ignores the opportunities of enhancements afforded by new materials that can be exploited in re-engineering and upgrading existing aircraft, as stated earlier. Further, the fact that military propulsion materials developments migrate into the nation's commercial engine manufacturing base keeps U.S. engine companies competitive on the world market. In each of the programs mentioned in Section 2.7, materials that developed to higher TRLs had a legacy; they did not materialize out of thin air. The present section discusses the elements that keep materials candidates progressing through a string of programs.

As one element there must be, for lack of a better descriptor, a path to development. A path to development can involve milestones and linkages from one program to another. However, the phrase also means that the steps needed for materials, process, and application development are thought out and ordered. For example, materials property issues, processing problems, and design issues need to be recognized, and approaches and timing to solve these issues need to be laid out in a roadmap format. The path to development must, on the one hand, be rational, clear, and well defined, but on the other flexible enough to take advantage of new opportunities or applications. This path includes assessing risks and risk-reduction strategies for new materials. Although the roadmap must not be rigid, it needs to be laid out so that there is a path through the various levels of research, development, and application (6.1, 6.2, and 6.3 funding levels). Absent any particular program, some individual or group of people must decide what needs to be done to take a promising candidate from the status of candidate to that of a viable material for consideration for insertion that can fit a system development cycle time. If this element, the path to development, were to be fit into the notional development process, it would be at the stage labeled "Selection for Advanced Development Laboratory" in Figure 2.5.

Materials innovation is required at all stages, but more so in early development. Innovation must be fostered at an early stage before specific engine requirements are laid out. Early identification of needs, time to innovate, and time to prove or disprove the worth of innovations and developments are all critical. The role of computation and modeling in reducing development time is gaining rapidly in importance in materials innovation and may allow for the exploration of innovative ideas without the commitment of funds eventually needed to proceed to experiments.

Development must be sustained over a significant period of time, often 10 to 20 years or more. Although programs and needs change, steps need to be taken to review technologies and to capture knowledge so that the effects of gaps in funding and/or time are minimized. Material or technology champions or visionaries are critical here, as are methods of capturing and transferring knowledge. Too often materials developments are stalled because of funding shortfalls or changing requirements. Short-term issues should not interfere with ensuring that materials are ready for long-term needs. The importance of sustained funding cannot be overstated. *Whatever the funding level is, it must be stable and predictable. Periods of "boom and bust" must be avoided,* as they lead to failure in delivering product and to uncertainty of purpose in establishing long-term commitments to developing promising materials and the processes needed to manufacture them.

As a material becomes more understood and is ready to be taken into a program shown in Figure 2.10 in the non-AFRL section, and as a technology matures and production and scale-up are needed, a partnership between government and industry becomes increasingly important. Industry has the experience to manufacture in a cost-effective manner, and the economic impetus to generate commercial applications for a technology allows for faster development.

Once a material moves into a program shown in the non-AFRL section of Figure 2.10, the application must be significant, and the benefit must be clear to all parties in terms of cost, performance, or safety and acceptance of risk. Matching the benefits of a new materials technology to engine needs must be ongoing. Needs change and benefits of a technology might not always be realized, and developers must be agile in identifying and responding to changes.

The technology must provide a significant advantage over existing lower-cost or lower-risk solutions. A compelling case has to be made for the advantages of a technology in terms of performance, cost, risk, and time. A clearly laid out path for the development and the continual review of the technology and competing technologies allow for clear articulation of the benefits and development and insertion costs to the end user.

The risk must be manageable or at least relatively low compared to the benefits and costs. Identifying and reducing risk early are critical. Early materials development (low TRL number) is required to mitigate risk early, or new materials will never be used.

Industry involvement and technology transfer are required, and the timing is critical—a technology can fail if commitment is either too early or too late. Full-scale development to use a material before it is ready can result in a perception of failure and can lead to discarding a material because of insufficient development or an inadequate property database.

There must be a manufacturing capability that has a path forward and solutions to the manufacturing challenges. The involvement of industry early is required, but so too is investment in processing and manufacturing technology. The identification of manufacturing obstacles and risks early in the program, combined with the identification of a manufacturing approach and partners, is critical.

There must be a compelling business need and a reward in order for a corporation to get involved and to produce the innovation for both government and potentially commercial applications. The government's business need is different, as it is focused on performance and cost, but equally compelling in determining the business case.

The common themes for successful materials development discussed in this section are listed below:

- A path to development;
- Materials innovation;
- Sustained development;
- A partnership: government and company;
- An application or need;
- A significant advantage;
- Low risk;
- Corporate involvement: timing is important;
- Manufacturing capability: a path forward and a solution to manufacturing challenges; and
- A product: business opportunity.

2.8.3 Further Discussion of the Role of Funding and Champions

As mentioned above, funding, at a sustained and appropriate level, is required for successful materials advancement, development, and insertion, but it is not the only reason for success or failure. The funding must be planned, aligned with the real risks and needs, and consistent. The funding challenges also require hard choices, in that less successful or less promising programs must be cut. However, it is critical that the knowledge of these technologies be maintained, as timing may be the only issue and future applications might require that technology.

The role of the visionary or champion of a new technology is critical, as the path to implementation is long, and a champion is usually necessary to obtain funding and find and match new technology to needs. The long time frames imply that management should be forming teams to match experienced personnel with new ideas and provide experience in developing technologies.

Fostering all of the above ideas, interactions, partnerships, and personnel combined with identifying and obtaining funding and matching the technology to an application requires sustained commitments from management at all levels, plus long-term plans that are flexible enough to accommodate new challenges.

Research and development at the lowest TRLs or low on the DOD 6.1 to 6.2 scale may not necessarily be aimed at specific applications. However, as the technology matures it is important to begin taking a more systems-oriented approach. Although designs and requirements may not be strictly defined and may be changing, having requirements to work toward and to focus technology development can be critical in increasing the likelihood of success. An example of this is the changing directions that flow through Air Force requirements. The emphasis in the IHPTET Program, and to a lesser extent in the VAATE Program, was primarily on performance, with high-speed flight as the focus. In high-speed flight, ram recovery temperatures present at the front face of the compressor start out much higher than in lower-Mach-number flight. When the temperature ratio through the compressor is added, the requirement for high-temperature materials for the final stages of the compressor becomes important. In recent years, the emphasis has shifted away from high-speed flight and toward increased efficiency at lower-Mach-number flight. Efficiency leads to higher compression ratios, so now high-temperature materials have become important again due to the higher compression ratios. This is an example of why the anticipation of materials capabilities, while associated with a forecasted need, should also be able to anticipate similar materials challenges even in a changing requirements environment.

2.9 EVOLUTION OF MATERIALS PROGRAMS AT U.S. UNIVERSITIES

2.9.1 Educational Structure: The Changing Environment and Preparation

Prior to the 1950s, the academic study of materials was addressed by separate departments focused on training either metallurgists or ceramists. The field of metallurgy focused on mineral beneficiation and the refinement of metals, as well as on processing, microstructural characterization, and the mechanical properties of metallic alloys. In turn, industry used these metallic alloys in the design and fabrication of products. As the understanding of metals evolved, so did the range of alloys available. The curriculum of metallurgical departments corresponded with customer needs or technology development.

In the late 1950s, the Soviet Union's successful launch of *Sputnik 1* had a chilling effect on U.S. engineering. This achievement was seen as a sign of weakness in the domestic scientific and engineering research and educational communities. One significant side effect was that some U.S. universities re-evaluated their engineering programs, including metallurgical engineering, and committed to revitalizing these programs with a greater insertion of science. Materials science achieved greater prominence within metallurgy departments and ultimately led to many departments changing their names to "Materials Science and Engineering" (MSE). Concurrently, foundry and mechanical processing laboratories were replaced with

TABLE 2.3 Trends in Titles of Materials Departments at U.S. Universities, 1964-1985

	Number of Departments, by Year		
Department Title	1964[a]	1970[a]	1985[b]
Minerals and Mining	9	7	5
Metallurgy	31	21	17
Materials	11	29	51
Other	18	21	17
Total	69	78	90

[a]Compiled from 1964-1970 *ASM Metallurgy Materials Education Yearbook*, J.P. Nielsen, ed. Metals Park, Ohio: American Society for Metals.

[b]Compiled from 1985 *ASM Metallurgy Materials Education Yearbook*, K. Mukherjee, ed. Metals Park: Ohio: American Society for Metals.

SOURCE: Reprinted from National Research Council, 1987, *Advancing Materials Research*, Peter A. Psaras and H. Dale Langford, eds. Washington, D.C.: National Academy Press, Table 2, p. 37.

those involving electron microscopy, single-crystal growth, and semiconductor processing laboratories, among other scientifically focused activities. Toward the end of the 1960s, polymeric processing and biomaterials were introduced into many university materials programs.

In this environment, as materials usage changed (i.e., electronic materials, polymer composites, and metal-matrix composites), complementary course work was incorporated. The MSE departments combined topics from engineering as well as from the sciences of chemistry and physics. Thus the new focus of MSE shifted from the production and refinement of materials, especially metals, to an emphasis on the interrelationship between structure and properties.[18] MSE departments were no longer found exclusively in engineering colleges, with programs emerging in colleges of arts and sciences as part of physics or chemistry departments. The trend toward more general "materials" departments over the past few decades is summarized in Table 2.3.

MSE departments never achieved enrollment rivaling that of the major engineering disciplines, but their reach and funding sustainment were enlarged by offering service-based courses in the basics of undergraduate materials science courses to other engineering disciplines. Nonetheless, the MSE curricular diversity makes it difficult to sustain a faculty large enough to cover the full complement of graduate course offerings. This has caused the recent absorption of several MSE

[18] National Academy of Sciences. 1975. *Materials and Man's Needs: Materials Science and Engineering, Volume III, The Institutional Framework for Materials Science and Engineering,* Supplementary Report of the Committee on the Survey of Materials Science and Engineering. Washington, D.C.: National Academy of Sciences, p. 155.

departments back into basic engineering disciplines such as aerospace, biological, electrical, chemical, mechanical, or civil engineering. The colleges that have retained their MSE departments are addressing new topics, such as nanomaterials and bioengineering applications, while trying to maintain viability primarily on the strength of their funded graduate-level research. Figure 2.12 illustrates an increase in the number of degrees granted within the MSE fields; however, when considering the corresponding increase in MSE disciplines, the pool of PhD candidates for structural materials is actually declining.[19]

Thus, over the short history of MSE as an academic discipline, its emphasis has experienced many changes. Where separate departments existed for metallurgical and ceramics engineering, the faculty was brought together for the interdisciplinary study of MSE. As MSE departments grew and graduated new PhDs without background in the individual disciplines, the current offerings of MSE lost depth in practical experience and/or science of specific materials.

In the 1975 report *Materials and Man's Needs: Materials Science and Engineering Volume III, The Institutional Framework for Materials Science and Engineering,* from the National Academy of Sciences, the question was posed as to whether a truly interdisciplinary MSE program would develop or whether it might become a group of materials science offerings affiliated loosely with one another.[20] This question might be more properly stated to ask whether the real difficulty in achieving genuine intellectual innovation in curricular matters is caused by the competing interests of other existing departments.[21] Current emphasis on electronic materials, biomaterials, and nanomaterials, fueled by funding thrusts, leaves little room for fundamental studies in traditional areas such as structural, high-temperature materials.

2.9.2 Structural Design Approach

Historically, metallurgical engineering has been associated with the mechanical engineering departments tasked with meeting a common goal of training engineers to convert ore into raw materials to produce components and devices. Basic design was limited to a few metals, such as steel, which were considered homogeneous, and a relatively simple stress analysis could be undertaken based on the theory of elasticity. As new alloys have become available and the needs of the transportation industry have increased, so have the design requirements to include structural reliability and long service life. The jet engine, first demonstrated in the 1940s, has

[19] Science and Engineering Degrees by Discipline, compiled by the National Science Foundation. Available at http://www.nsf.gov/statistics/. Accessed July 2009.

[20] National Academy of Sciences. *Materials and Man's Needs: Materials Science and Engineering, Volume III,* 1975, p. 213.

[21] Ibid., p. 214.

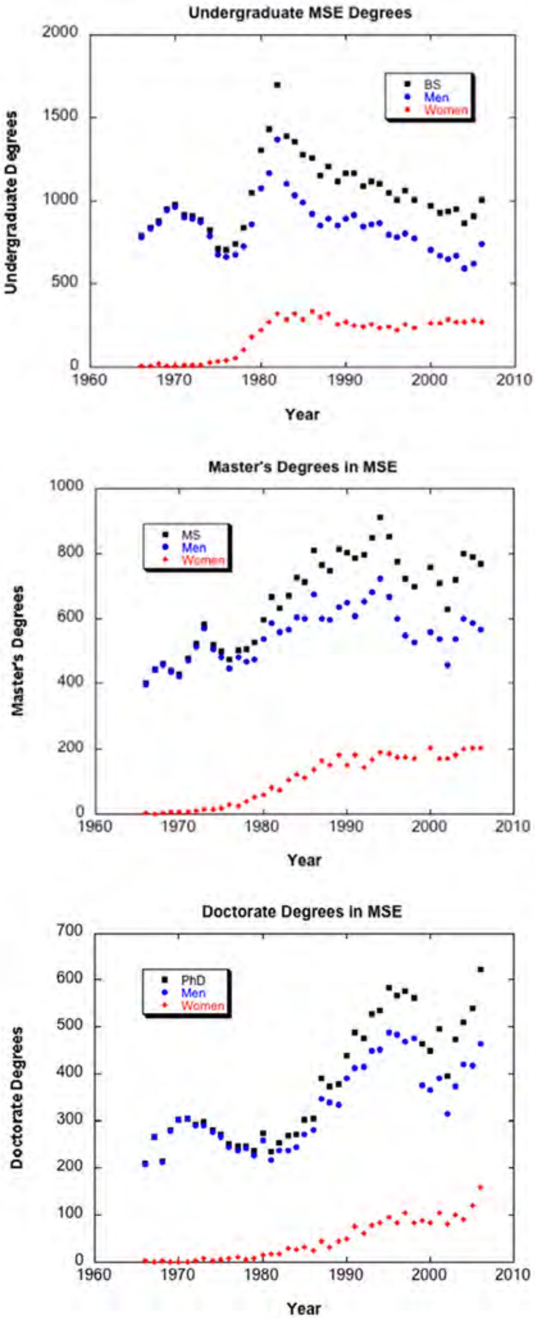

FIGURE 2.12 Materials science and engineering (MSE) degrees awarded for (top) undergraduates, (center) master's level, and (bottom) doctoral level. SOURCE: National Science Foundation Report NSF 08-321; available at http://www.nsf.gov/statistics.

made it necessary for design and manufacturing engineers to adapt an entirely new approach to materials. To increase performance, engine designs continue to demand more-heat-resistant materials to realize more efficient engines. However, the newer materials are more difficult to cast, forge, and machine and have introduced difficult challenges for engineers who are involved in their production.[22]

Based on past history, engineers have not been taught to respond to design challenges by the heterogeneous placement of materials properties of interest where needed. The use of Integrated Computational Materials Engineering (ICME) is helping designers input the operational constraints into the design process, but while still treating the material as homogenous. There is a need to expand the usefulness of ICME by bringing it down to the materials design level. This requires an interdisciplinary approach to bridge the science with the engineering. This approach is reflected by the use of more IPDTs in industry than in universities, which have to cross departmental and college lines to build interdisciplinary teams.

The difficulty in crossing departmental or college lines is felt by engineering students who take a vast majority of their engineering courses within their home department. This contrasts with industry, in which teams of engineers with varying backgrounds are assigned to a project or product team. Too often an engineer's first job is also the first time that he or she is required to work within a team capitalizing on the complementary strengths of team members from various backgrounds. The Accreditation Board for Engineering and Technology (ABET) has recently included requirements for interdisciplinary courses or projects to better encourage and prepare students for the work environment; however, this seems to be at odds with the push by university administrators to reduce credit hours for engineering undergraduate degrees. As fundamental materials science courses are eliminated from the curriculum, the future engineers are not being trained to work with or embrace revolutionary materials.

Within the engineering design field, ICME uses various models on a common platform to evaluate interactions between the responses of a material in a component and its environment. This has shortened the design time for aircraft structures, turbine engines, and automobiles. While industries have successfully used integrated product development (IPD) and multidisciplinary optimization (MDO), the science of materials development has not been part of this computerized optimization process. Although materials development is not part of the computerized optimization process in the above methodologies, guidelines for advanced materials requirements, such as the need for lightweight materials that can withstand higher operating temperatures, are generated.

In a study by the National Research Council titled *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness*

[22] Ibid., p. 168.

and National Security,[23] the committee concluded that while ICME efforts have significantly shortened the development time for various components, these efforts have not involved materials development. Companies such as Ford Motor Company, Alcoa, Inc., Howmet, and PCC Airfoils, LLC., have funded internal efforts to model the microstructural response of a material with the processing to shorten development times. Developing standards for materials development would help integrate these codes into a collaborative framework. A funding effort toward the national integration of scientific models and a collaborative framework are required to promote shorter cycles for materials development.

2.9.3 Use of Computational Modeling Across Length Scales

Materials science and engineering developed based on processing, structure, and properties in a pre-computerized world. The field of computational modeling has advanced in other engineering disciplines such as structural and fluid dynamics. Sciences have their share of ab initio and molecular-level dynamics to study atomic-level interactions. But with the main thrust of MSE split among processing, structure, and properties, it becomes more difficult to integrate not only across length scales but also across separate research areas. With the lack of standardized MSE undergraduate programs, the root of computational modeling is not established.

Lessons learned from other disciplines in fields that achieved successful integration conclude that they share certain advantages.[24] Successful integration relies on cohesive data structure, common mathematical framework, and well-defined objects for investigation. The length-scale issues require the linking of codes at various length scales that do not share a common mathematical framework, a cohesive data structure, or a common academic discipline.

As concluded in a recent study from the National Research Council on ICME, "the future of MSE is at a critical crossroad."[25] The MSE community's embracing of the ICME methodology could substantially shorten the current 20-year materials development time. Although the constraints of diverse materials systems strongly influence product design, these systems are currently considered outside the multidisciplinary design loop.[26] Thus a cultural change is needed to include materials in the optimization process.

The successful integration of the science and engineering of materials development requires codes for capturing the physical behavior from nanoscale atomic-

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[23] National Research Council. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press.

[24] Ibid., p. 37.

[25] Ibid., p. 35.

[26] Ibid., p. 63.

level interactions to multiphase materials at the macroscopic scale. No longer the domain of a single discipline, integration across length scales and mathematical platforms will require collaboration and cooperation. The field of computational materials science (CMS) is being employed at various length scales to describe properties of materials based on semi-empirical, ab initio, and atomic and molecular-scale simulations. Successful integration will require communication between experimental materials research and the computer modeling of advanced materials and applications. The long-term goal of CMS is to provide a predictive understanding of materials behavior.

Fundamental relationships are the basis for the computer codes currently employed in engineering. Analytical equations are solved and integrated into a mathematical frame that applies these relationships over complex two- or three-dimensional spaces. For instance in computational fluid dynamics (CFD), the Navier-Stokes equations are solved and integrated with various meshing schemes to track elements of fluids as they flow through space defined by a mesh in either Eulerian or Lagrangian coordinates. The physics of the fluid is also often incorporated into CFD analysis.

A similar scenario is used in evaluating the response of a complex structure or component to either static or dynamic loading. Mechanical properties of a material are collapsed into an equation that is tracked over complex two- or three-dimensional spaces, again using a meshing scheme defined by either Eulerian or Lagrangian coordinates. Various equations have been developed to include terms defining the response of the material over ranges of temperature and strain rates. Extensive mechanical testing is required to fit the material-behavior equations and determine material-specific constants. Although the physics of the material is not incorporated, research is currently examining the applications of physics and chemistry to define the atomic-level structure and its response to load and environment. The current state of the art makes use of multiscale modeling to predict the response of heterogeneous materials. Currently, databases of materials properties are developed for monolithic materials at the length scale at which they can be considered homogenous. The effects of varying the processing are considered proprietary, and dissemination of this information is limited. This limitation illustrates the infancy of CMS and of linking databases beyond monolithic materials.[27] Efforts to link the multiscale modeling to the physical level of atoms and molecules must continue. Establishing a roadmap for how these various analytical models can be linked in a mathematical format will evolve as these models progress.

Scaling up from the atomic level to incorporate the physics and chemistry of the structure in a solid material will result in more-predictive material models. Currently, this research is actively funded. Once the physics and chemistry interactions

[27] See http://kriven.mse.uiuc.edu/. Accessed November 2009.

are accurately modeled using semi-empirical, ab initio, or atomic- or molecular-scale simulations, additional development will be required to link the atomic-level physics with the macro-level prediction of behavior, including the influence of defects. Research over the past 50 years has greatly expanded the understanding of materials properties controlled by competing mechanisms, which are strongly influenced by defects at varying length scales. The evolution of physically accurate predictive models will require a first-principles foundation.

2.9.4 The Role of Funding in Graduate Education

Graduate education is heavily influenced by two things: the availability of facilities and the availability of funding. As mentioned above, the focus of MSE is split between engineering (i.e., materials properties and applications) and sciences (i.e., the fundamental understanding of materials behavior). The emphasis on various aspects of engineering and sciences content in the preparation of graduate students depends on changes in the industrial sector (i.e., the job market) and the role of federal funding. Advances in polymers and aircraft structures during World War II carried the development of materials to meet national security challenges until the end of the Cold War in 1991. The largest source of national R&D funding both in industry and in academia since World War II has been the federal government.

Table 2.4 summarizes the areas where top federal funding agencies—including the DOD, the Department of Energy (DOE), NASA, the Department of Health and Human Services (HHS), the National Science Foundation (NSF), the U.S. Department of Agriculture (USDA)—have concentrated their resources as documented for fiscal year (FY) 2008.[28] The DOD provided the majority of funding for materials engineering, whereas the majority of funding for physics research came from various funders: DOE, NASA, HHS, and NSF. Although the funding profile has remained constant, federal government funding is decreasing as industry funding is seeing an increase. This affects ease of access, as findings obtained in government-funded programs can be shared, whereas industrial-sponsored research is often considered proprietary.

Physics research funding declined throughout the 1990s, reflecting the cancellation of several major projects such as the supercollider (in 1993).[29] A relatively steady level of funding for materials engineering has existed over the past 25 years, as shown in Figure 2.13. However, as noted previously, the number and diversity of subdisciplines within MSE have increased. Thus, with competing interests, the

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[28] See National Science Foundation, *Science and Engineering Indicators: 2010*. Available at http://www.nsf.gov/statistics/seind10/start.htm. Accessed November 2009.

[29] See http://en.wikipedia.org/wiki/Superconducting_Super_Collider. Accessed September 2009.

TABLE 2.4 Top Federal Funders of Research by Field, Fiscal Year 2008 (percent of total funding)

	DOD	DOE	NASA	HHS	NSF	USDA	Other
Engineering							
Aeronautical/Astronautical	**44.7**	2.3	22.2	0.8	3.4	0.0	10.9
Chemical	21.9	17.8	2	15.7	26.8	1.7	10.2
Civil	13.2	7.5	3.4	2.6	22.9	1.3	**48.8**
Electrical	**44.8**	3.2	2.9	4.0	22.6	0.0	6.8
Mechanical	33.6	15.5	4.5	4.1	15.5	0.3	10.5
Metallurgy and materials	**44.4**	13.4	2.1	2.7	23.8	0.5	12.8
Physical sciences							
Astronomy	3.7	2.3	**55.6**	0.3	21.7	0.0	10.0
Chemistry	11.0	7.2	1.3	**43.5**	28.1	0.5	6.4
Physics	15.0	26.5	11.7	2.8	32.9	0.2	5.6
Life sciences							
Biological	2.5	1.0	0.6	**80.9**	6.7	3.0	4.6
Agricultural	1.5	2.9	1.3	7.9	9.5	55.9	19.4
Medical	3.0	0.4	0.4	**91.0**	0.4	0.3	4.0
Mathematics and computer sciences							
Mathematics	10.8	2.9	1.1	25.6	**47.2**	0.9	5.6
Computer sciences	29.3	3.3	2.0	5.3	**42.4**	0.3	11.2
Environmental sciences							
Atmospheric sciences	7.1	5.0	30.0	0.3	27.0	1.2	26.7
Earth sciences	7.0	9.6	17.7	1.7	33.0	9.0	21.6
Oceanography	11.4	0.7	2.9	2.0	**42.4**	0.9	37.0

NOTE: Percentages greater than 40 percent are in bold to highlight dominant funders. Acronyms are defined in Appendix F.

SOURCE: Adapted from National Science Foundation. 2010. Available at http://www.nsf.gov/statistics/seind10/appendix.htm#c5.

amount of funds for materials systems actually declines when spread over a broader range of topics.

Several programs have been started as attempts to more closely align graduate-level education in MSE with industry needs and to address the lack of process knowledge in the graduate-student pipeline. These programs were specifically aimed at increasing interactive research between universities and industry in materials development. Examples include the following: the Committee on the Survey

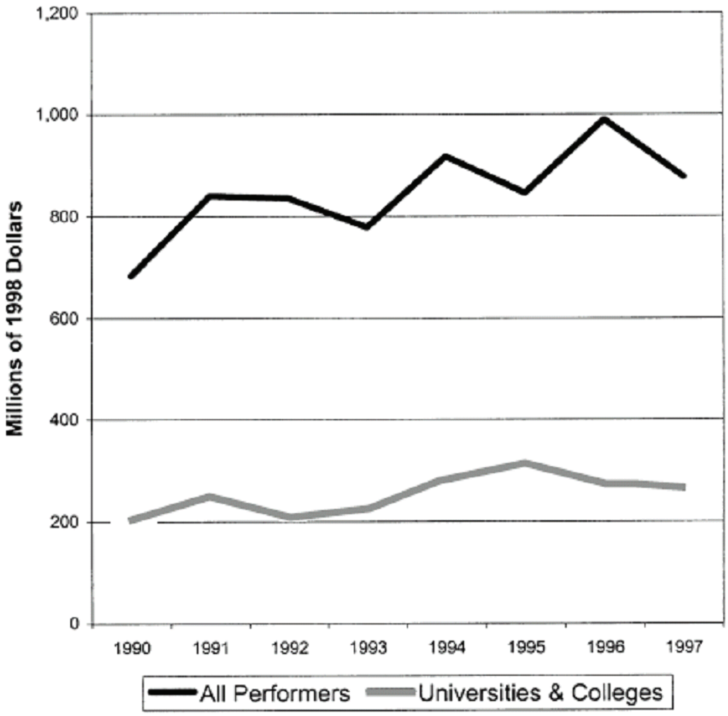

FIGURE 2.13 Constant-dollar trends in federal funding of materials engineering research, FY 1990-1997. SOURCE: Reprinted from National Research Council, *Securing America's Industrial Strength*, Washington, D.C.: National Academy Press, 1999, Figure A-13.

of Materials Science and Engineering (COSMAT)[30] survey in 1975, Advanced Research Projects Agency (ARPA) programs requiring that the research products be of major DOD interest, NSF centers, and NASA centers.

In a National Research Council report on materials science and engineering for the 1990s, it was observed that the programs mentioned above had a downside regarding the money spent as compared with the results.[31] The rationale for this conclusion includes the following considerations: the monetary infusion had produced no evidence of impact on the production of advanced degrees; despite intentions

[30] National Academy of Sciences. 1975. *Materials and Man's Needs: Materials Science and Engineering, Volume III, The Institutional Framework for Materials Science and Engineering,* Supplementary Report of the Committee on the Survey of Materials Science and Engineering. Washington, D.C.: National Academy of Sciences.

[31] National Research Council. 1989. *Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Material.* Washington, D.C.: National Academy Press.

to the contrary, no mechanism for effective sharing of facilities within universities, which currently largely exist only in industry, had developed; and the degree of interdisciplinary education that was developed by these programs fell short of that expected and practiced in industry, although it did improve over what had been present in traditional departments.[32] However, as will be noted in Chapter 3 of the present report, this reduction in available facilities in industry and academia is being offset at the present time by the user centers established at national laboratories.

Regardless of the perceived failings of the programs referred to above, it is important to point out that decisions on both the availability and the potential use of results from research grants made to universities at the 6.1 level have a direct and profound impact on the direction of university programs. This issue is addressed in Chapter 5, but it is important to understand the funding emphasis of the university grants from the Air Force Office of Scientific Research and to compare this to the needs for materials for aerospace propulsion that will be presented in Chapter 3.

2.9.5 Summary of Observations Specifically Related to Universities

The current emphasis within universities on electronic materials, biomaterials, and nanomaterials, fueled by funding thrusts, leaves little room for fundamental studies on structural, high-temperature materials.

The MSE community's embracing of the ICME methodology has the potential to shorten materials development times. Although the constraints of diverse materials systems strongly influence product design, these systems are currently considered outside the multidisciplinary design loop.[33] Thus a cultural change is needed in order to include materials into the optimization process. ICME methodology must be incorporated into the MSE departments within universities. However, as the presence of MSE departments in universities continues to decline, this opportunity may be lost.

For the propulsion materials enterprise to benefit from the injection of modeling and simulation tools at many levels, this methodology must be implemented at U.S. universities. At the most basic level, models can be used to increase the understanding of the behavior of current materials—mechanical behavior, environmental behavior, microstructural stability, and so on. If correctly formulated and validated, models can be predictive of incremental improvements or, best of all,

[32] National Academy of Sciences. 1975. *Materials and Man's Needs: Materials Science and Engineering, Volume III, The Institutional Framework for Materials Science and Engineering,* Supplementary Report of the Committee on the Survey of Materials Science and Engineering. Washington, D.C.: National Academy of Sciences, p. 212.

[33] National Research Council. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Washington, D.C.: The National Academies Press, p. 63.

can point to entirely new directions for materials development. However, graduates of U.S. universities must be trained in these areas prior to joining the workforce in order to implement future change.

As was well documented by case studies in the report of the NRC's National Materials Advisory Board titled *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security,*[34] the integration of design and materials processing models can lead to components that are optimized for mechanical properties at the lightest weight possible. Furthermore, if the statistical variability inherent in materials properties can be understood and modeled in a particular material system, then similar materials could be considered to behave in a similar fashion, and the burden of testing prior to the implementation of analogous materials could be lightened. These scenarios could speed the inclusion of "newer" materials into systems, provided that these newer materials were similar to the current bill of material. The insertion of a completely new class of materials—for example, ceramic-matrix composites—would have to be accompanied by considerable materials testing in relevant environments.

The ultimate question is whether extensive modeling and simulation can take the place of materials insertion into demonstration engines, and the answer has to be: It depends. If the proposed new material is analogous to a material already used in a current system but with improved properties that will result in life extension, then the answer should be Yes. But if the material to be inserted is radically different, such as a CMC, or if a designer wishes to take advantage of a new suite of properties in a metallic material, then the new material would have to be demonstrated, first in a rig but ultimately in a demonstrator engine. Only an engine test can provide the actual environment in which a material must operate—temperature, pressure, gas environment, and stresses both static and cyclic.

2.10 PROPULSION MATERIALS RESEARCH SUPPORT FROM THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

It is clear from the preceding discussion of MSE programs that funding opportunities have a direct impact on graduate and faculty research programs at U.S. universities with respect to both in the types of projects worked on and as the preparation given to graduates. This recognition has always been at the heart of the Air Force's support for university research. The present character of the Air Force Office of Scientific Research, which fulfills the Air Force's primary role in university research funding, has evolved extensively from its first incarnation

[34] National Research Council. 2008. *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security.* Committee on Integrated Computational Materials Engineering. Washington, D.C.: The National Academies Press.

in response to the von Karman Commission Report, funded by the Army Air Corps under Gen. Henry "Hap" Arnold, U.S. Army Air Corps, shortly after World War II. AFOSR's present function and format can be traced to a number of major changes in the Air Force. The most significant events included the dissolution of the Aerospace Research Laboratory in the 1970s, leaving the Frank J. Seiler Research Laboratory, collocated with the Air Force Academy in Colorado Springs, as the only laboratory in the Air Force with a charter to do basic research exclusively. By then, the Seiler Laboratory reported directly to the AFOSR. Eventually the Seiler Laboratory was also dismantled, in the 1990s.[35]

With the dismantling of these laboratories, basic research—that is, 6.1 research—within the Air Force laboratories (now a single Air Force laboratory, the AFRL, with various directorates) is performed under grants from the AFOSR. The AFOSR now functions as a separate operating agency of the AFRL within the Air Force Materiel Command, charged with the centralized management function for Air Force basic research, to accomplish the Air Force goals outlined for scientific and engineering research. These basic research goals include the maintaining of technological superiority in scientific areas coordinated to Air Force requirements, the prevention of technological surprise, and the maintaining of a strong science and technology infrastructure, with all areas complementing the overall national research effort.[36]

Until the early 1990s, discretion with respect to which research projects were supported by the AFOSR was generally left to the various program managers, who were (and continue to be) required to present and defend their program portfolios at annual reviews. Since the early 1990s, the AFOSR has been required to submit proposals to an external review board for vetting and grading before the program manager is able to exercise his or her discretion in choosing which proposals are to be funded. Still, the actual character of the research sponsored by the AFOSR is heavily dependent on the personalities overseeing the various research areas as well as on the upper management of the AFOSR, which is civilian. In the area of structural materials for propulsion, a number of changes have also taken place that formed the present character of the sponsored programs. Most notable is the elimination of the Metals Program as a separate program element, subsuming its projects and those of the Ceramics Program into the Aerospace Materials Program. The following information is taken from AFOSR's most recent board agency announcement (BAA):

> The objective of basic research in High Temperature Aerospace Materials is to provide the fundamental knowledge required to enable revolutionary advances in future Air Force technologies through the discovery and characterization of

[35] See http://www.wpafb.af.mil/library/factsheets/factsheet.asp?id=8976. Accessed April 20, 2011.

[36] Adapted from "Air Force Office of Scientific Research: A Brief Organizational History." See http://www.wpafb.af.mil/library/factsheets/factsheet.asp?id=8976. Accessed January 11, 2005.

> high temperature materials (nominally temperatures above 1000°C) including: ceramics, metals, hybrid systems including composites. Applications of these materials include air-breathing and rocket propulsion systems, airframe and spacecraft structures and hypersonic vehicle systems. Specifically, the program seeks proposals that advance the field of high temperature materials research through the discovery and characterization of new materials that exhibit superior structural and/or functional performance at temperatures above 1000°C. Representative scientific topics include the development and experimental verification of theoretical and computational models of materials discovery, characterization methods for probing microstructural evolution at elevated temperatures and mechanics of materials at elevated temperatures. There is special interest in fundamental research of high temperature materials focused on understanding combined mechanical behaviors; e.g. strength and toughness as a function of thermal and acoustic loads. This focus area will require the development of new experimental and computational tools to address the complexity of thermal, acoustic, chemistry, shear or pressure loads as they relate back to the performance of the material.[37]

As stated at the beginning of the BAA, "AFOSR plans, coordinates, and executes the Air Force Research Laboratory's (AFRL) basic research program in response to technical guidance from AFRL and requirements of the Air Force; fosters, supports, and conducts research within Air Force, university, and industry laboratories; and ensures transition of research results to support USAF needs."[38] Thus, there is a clear charge to support efforts that are relevant to Air Force needs and requirements and to ensure transition; however, it has been this committee's finding that the AFOSR's focus is on long-horizon-type efforts that, as stated in a briefing to the committee,[39] are interpreted as having a 20-year horizon. The association with the Air Force needs seems to be tied to AFRL's Focused Long Term Challenges rather than on direct input from AFRL directorate personnel. Further, to the knowledge of the committee, no transitional research is even being considered for funding. "Transitional" is interpreted here to mean moving a technology into the high 6.1 level, or at least that the Air Force has sufficient knowledge of transitional activities outside AFOSR's funding portfolio to ensure that some of the AFOSR's funded efforts can be considered for near-term transition.

Testimony heard by this committee showed some frustration by directorate personnel in funding some of their in-house, 6.1 efforts. More surprising to this committee was the fact that these personnel saw the AFOSR as their only source of 6.1 in-house funds, being required to submit proposals to the AFOSR to be de-

[37] See http://www.wpafb.af.mil/library/factsheets/factsheet.asp?id=9222. Accessed November 2009.

[38] See http://www.wpafb.af.mil/shared/media/document/AFD-100217-027.pdf. Accessed November 2009.

[39] "Air Force Materials Needs for Future Military Aerospace Propulsion," briefing to the committee by Joan Fuller, AFOSR, Washington, D.C., July 20, 2009.

cided on through comparisons with other proposals on a competitive basis at the AFOSR. Nowhere did the committee get the impression that the AFRL Materials and Manufacturing Directorate and Propulsion and Power Directorate would, by design, provide input to the formation of technical guidance from AFRL and requirements of the Air Force for which the AFOSR provided fundamental research sponsorship.

It is clear from briefings to this committee that the AFRL's directorates are somewhat dissatisfied with the backgrounds of graduates educated at U.S. universities. Further, it is clear that the emphasis in altering these backgrounds can be directly influenced through the funding of grants to universities by the AFOSR, but these apparent needs within the AFRL and the types of graduate research funded at universities appear to be in a disconnect. It is not surprising that this disconnect exists, because most of the practices by the AFOSR were developed over a period of time during which the infrastructure in government, industry, and universities was in its heyday. At that time, universities were thought of mainly in terms of providing a stream of graduates with the appropriate backgrounds to work in industry and government laboratories. Research from universities was considered to be interesting but not of immediate impact, and most of the advances in materials were attributable to researchers in the engine manufacturing and materials supplier laboratories.

In some instances specific program managers within the AFOSR were in close tune with Air Force needs and were able to make immediate impacts on ongoing Air Force development needs. One of these was mentioned earlier in this chapter regarding composites. Another initiative sponsored within the AFOSR Metals Program in 2000 that had a direct impact on materials development was the AFOSR multiyear initiative Materials Engineering for Affordable New Systems (MEANS), which was intended to sponsor basic research for the expansion of scientific capability to develop and to employ analytical models of material behavior for use in design software. Part of the objective of MEANS was to develop models of materials that could be used to calculate behavior under various operating conditions, thus reducing the amount of repetitive and empirical testing then required for building a satisfactory database. Another important component was to develop software and design protocols that would permit the models so developed to be interfaced with current design software, allowing materials properties to be manipulated as part of the design space rather than to be constraints, as in the current paradigm for design.

The MEANS Program was initially established for 3-year, multi-investigator projects in metallic-, ceramic-, and polymer-based composite materials. The initiative was renewed for a second 3-year period beginning in 2003, and new projects were funded. All of these projects went to university-based investigators, with some collaboration with AFRL Materials and Manufacturing Directorate investigators. The importance of the MEANS Program is even now mentioned in industry and government.[40] An important point is that the MEANS Program had its emphasis on computational research rather than on laboratory-type work. There appears to have been an increasing shift in AFOSR-sponsored programs toward computational efforts.

It should be mentioned that the Office of Naval Research (ONR) also funds 6.1 work, but unlike the AFOSR, ONR also funds R&D that is 6.2 and above, within the Navy as well as at universities. Also, the ONR program manager is funding work that is directly related to current technical needs and issues.

2.11 FINDINGS

This chapter has traced the evolution of the process of development from concept to insertion over a period from the late 1960s to the present. The field of development of new structural materials for propulsion underwent a change from a heyday that peaked in the mid-1980s to the present ebb, which is due to a number of evolving shifts in paradigms: from materials for improved performance, to development free of risk, and concentration on things other than just performance. Also in the present climate, there is a *perceived* lack of requirements pull on technology to re-infuse or redirect existing funds into structural materials for propulsion. There is now a large cycle time required to move promising materials from early-concept, 6.1, levels to being viable candidates for insertion in new development engines; without either reducing this cycle time to be in sync with engine development cycle times or adapting to the new realities in a more inventive way, there will be no new materials available when new-capability engine development programs re-emerge.

Although near-term opportunities for new engine development programs do not appear to be on the horizon, it is almost certain that engine development opportunities will present themselves in time frames that coincide with materials development cycle times, be they in the re-engineering of existing airframes, the development of new bombers, or the development of high-performance unmanned vehicles, and other efforts. If quantum advances in performance are to be anticipated due to advances in materials and processes, which has been the historic trend (see Figure 2.3), then new types of materials other than metallics must be moved up the TRL ladder. This can be done only by interceding to change the present paradigms that have led to the drying up of the stream of new structural materials available for insertion consideration. These conclusions are summarized in the following list of specific findings supported by the material in this chapter.

There were many engine development programs in the 1980s. Starting in the 1990s, fewer engines have been and are now being developed, and these fewer

[40] Personal communication, Craig S. Hartley, El Arroyo Enterprises, LLC., October 8, 2009.

engine development programs emphasize low risk (high TRL), which discourages the use of revolutionary and high-risk material insertions. Demonstration-engine programs created to improve engine performance picked up where declining engine developments left off and afforded materials development insertion opportunities. However, continuing demonstration programs have de-emphasized materials development and plan fewer engines, and the acceptable risk level of these programs is low—that is, they have high TRL requirements.

Finding: The decline in new engine developments (i.e., requirements pull) and aversion to risk have led to a decrease in support and advocacy for the use of new materials in new engine designs.

Despite recent improvements in the materials development process—such as standardization of the process, tighter integration of design and materials activities, and emerging application of nascent ICME technologies—the materials-development cycle remains excessively long. During the same period in which those improvements were made in the materials development process, the introduction of computational methods and more-disciplined engine development practices shortened the engine development cycle. This means that even if materials candidates at relatively high TRL are available for consideration at the beginning of an engine development, the time needed to reduce the risk of a material's insertion no longer exists.

Finding: The development cycle for materials is considerably longer than that for engines; this is a deterrent and source of risk for the introduction of new materials into propulsion systems.

Historically, engine manufacturers and supplier researchers and facilities have been a major source of both invention and innovation for aerospace structural materials. However, driven in part by the decreasing opportunities for new engine developments and in part by aversion to the risk imposed by new materials insertions, a gradual decrease has occurred in the number of industrial researchers, laboratory facilities, and corporate investment in aerospace materials, which together have reduced the pace of aerospace materials innovation and the availability of new materials ready for materials insertion. The result has been the drying up of the candidate-material pipeline. The long-standing traditional, ad hoc materials development approach could not be sustained effectively as the aerospace propulsion industry matured, engine products proliferated, and competition, both domestic and global, intensified. Unstable funding and a lack of long-term funding commitments further accelerate this decline.

Finding: There has been a significant decline in overall infrastructure (facilities, equipment, skilled people, and so on) for materials and processing, further weakening the U.S. technology base in materials development.

Nontraditional aerospace materials, such as intermetallic alloys and ceramic composite materials, have been garnering increased interest in recent years. These materials offer significant insertion benefit. However, early development efforts do not seem to address the mitigation of the risks associated with revolutionary materials, including damage tolerance and new failure modes and their consequences, or the maturity of the manufacturing infrastructure. These new materials need to be fully understood prior to commitment and production insertion.

Finding: Newer structural materials that may show some promise or even the possibility for revolutionary changes, especially those discovered under AFOSR funding, are disconnected from continued efforts that begin moving them up the TRL ladder.

Although the AFOSR encourages its principal investigators to be aware of Air Force needs, at present AFOSR program managers focus on long-horizon technologies. Examples of closely tied cyclic interaction of all levels of 6.1 through 6.3 efforts in nonpropulsion materials have demonstrated the advantage of closer cooperation between the AFOSR and the AFRL. If the decline in materials candidates at sufficiently high TRL to impact future engine designs is to be reversed, the AFRL and the AFOSR must exercise the available flexibility in applying funding categories.

Finding: The present approach to developing new materials at the lower TRLs is inadequate for an environment with reduced infrastructure and advocacy.

Although the advance of aerospace metal alloys is decelerating, these materials will likely remain the materials of choice for critical turbine hardware. Whereas traditional advances were achieved by means of compositional and processing innovation, future advances will rely more on achieving improved property balance, local properties tailored to the requirements at critical locations within a component, and hybrid structures fueled in part by ICME technologies, but these improvements must be accompanied by research in processing them.

Finding: Insufficient research for processes affects even better-understood materials.

Linked to all of the findings above is the distinct change in the character of materials science and engineering programs, the type of research efforts, and the concomitant qualification of graduates at U.S. universities. Influenced in part by research grants administered by the AFOSR, some accommodation of university programs must take place if continued advances in structural materials for propulsion are to be expected.

Finding: Structural materials education and research at U.S. universities have declined, and this decline is threatening the strength of the domestic structural materials engineering workforce.

Although the overall funding for the general field of MSE increased somewhat during the 1990s as is demonstrated in Figure 2.13, the general impression among educators working on structural materials, as expressed by one such educator on this committee, is that since 1997 the funding in all of MSE has remained essentially level. At the same time, the number of areas of research in MSE has greatly increased, and so the funds going specifically toward structural materials have decreased.

3

Materials Development Assessment

The availability of critical materials for propulsion systems and innovative manufacturing processes and capacity have been key elements in creating and maintaining U.S. preeminence in military aircraft capabilities and have contributed significantly to the U.S. engine manufacturers' competitiveness in the global market.[1] The first six sections of this chapter provide assessments of the following: Section 3.1, the materials development process used for structural materials research and development (R&D); Section 3.2, the organizations in the Air Force Research Laboratory (AFRL) addressing materials R&D; Section 3.3, materials research and databases; Section 3.4, the importance of materials to the three types of propulsion needed for U.S. Air Force (USAF) missions; Section 3.5, the current global activities in propulsion structural materials; and Section 3.6, the past, present, and planned activities of the AFRL in propulsion structural materials. Sections 3.7 and 3.8 present, respectively, the findings and recommendations of the committee related to its materials development assessments.

3.1 DEVELOPMENT PROCESS FOR STRUCTURAL MATERIALS RESEARCH AND DEVELOPMENT

The Air Force's science and technology (S&T) process is illustrated in Figure 3.1. Basic research (6.1), applied research (6.2), and advanced technology

[1] National Research Council. 2006. *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs.* Washington, D.C.: The National Academies Press.

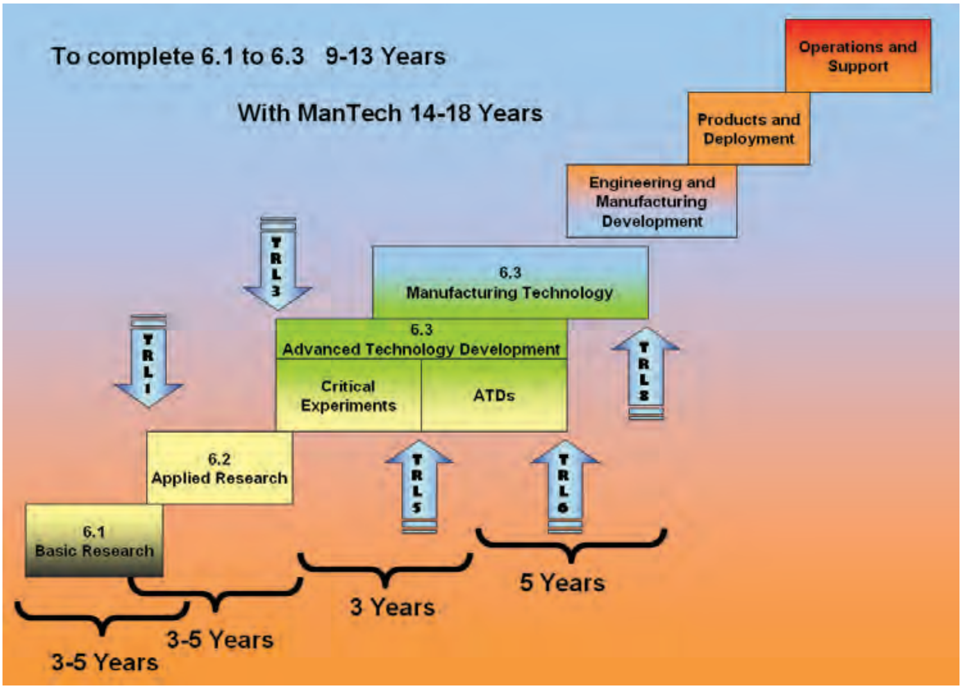

FIGURE 3.1 Air Force science and technology program. NOTE: Acronyms are defined in Appendix F.

development (6.3) constitute the parts of the S&T program that are managed by the AFRL. The S&T program seeks new ways of accomplishing tasks of military value and developing the underlying scientific and engineering principles involved. Individual S&T projects are not directed at developing new operational weapons systems, although they may support such development by solving specific problems. The 6.3 Manufacturing Technology (ManTech) element is the program of the Air Force that anticipates and closes gaps in manufacturing capabilities for the affordable, timely, and low-risk development, production, and sustainment of defense systems. The elements above 6.3 are the Air Force's Acquisition Program, managed by the system program offices.

Within the S&T program, basic research (6.1) is the systematic study directed toward greater knowledge or understanding in science and engineering of the fundamental aspects of phenomena and/or observable facts consistent with the Air Force missions, but without practical application of that knowledge and understanding. Applied research (6.2) is systematic study to gain the knowledge or understanding necessary to determine the means by which a recognized and specific need may be met; these efforts attempt to determine and exploit the potential of scientific discoveries or improvements in technology such as new materials, devices, methods, and processes. Advanced technology development (6.3) includes all efforts that have moved into the development and integration of hardware for large-scale or field experiments and tests. Advanced technology development demonstrates the viability of applying existing technology to new products and processes in a general way.

If a new material followed the exact path illustrated in Figure 3.1, a 6.1 program would last on average about 3 to 5 years, a 6.2 program would last about 3 to 5 years, and a 6.3 advanced technology development program would last about 3 years. The total S&T effort would thus be around 9 to 13 years. This time period assumes that no major issues would result in program delays; such issues could easily add several years to the process. If a ManTech program were factored into the process, the total time could easily reach 14 to 18 years or longer. It is possible that the Air Force S&T steps shown in the figure could be skipped altogether if a strong industry development effort completed the technology base work with internal funds. The nature of the work would remain the same, but would be funded by industry.

For noncritical components, materials that have already transitioned into a system and are subsequently modified typically require much less time for reinsertion than for the original development effort. In general, the 6.1 step is eliminated for reinsertion. The "tweaked" material may start at the late 6.2 or early 6.3 stage. In such a case, the time to transition into a system may be as short as 3 to 5 years.

For critical components, materials that have already transitioned into a system and are subsequently modified would also likely see the 6.1 step eliminated. The modified material may also start at the late 6.2 or early 6.3 stage. The 6.3 stage could be longer for critical than for noncritical applications owing to additional testing. In such a case, the time to transition may be as short as 5 years of S&T or as long as 8 years, especially if requalification is required.

Figure 3.1 is useful for illustrating the various elements of the S&T program and their relationships to the system customer (the three program elements in the upper-right-hand corner) and the various TRLs for each stage. However, a material's transition path, in which a new composition or process transitions sequentially from one totally isolated or independent element to another, as shown in Figure 3.1, does not represent the actual technology transition path that most materials and processes follow. There is no consistent formal path for a material's transition from basic research to applied research to system development to ManTech. For a new material, the S&T elements represented in Figure 3.1 could be working on complementary, parallel paths, with multiple programs in each. As the maturity level increases, including in production, work at an earlier stage may be necessary to address an unforeseen issue. This cyclical nature of materials transition is not unusual and in many cases is a known element of risk for high-performance applications. Modification of an existing material could require that multiple program elements (upper right, Figure 3.1) also be pursuing parallel, complementary paths. In all cases, continuous interaction among the program elements must take place for the transition to be timely and successful.

3.2 ORGANIZATIONAL ENTITIES OF THE AIR FORCE RESEARCH LABORATORY

The Air Force Office of Scientific Research (AFOSR), the Materials and Manufacturing Directorate, and the Propulsion and Power Directorate are the organizational entities that handle the development of new materials and their introduction into propulsion systems. The AFOSR manages the basic research investment (6.1 in Figure 3.1) and is a part of the AFRL. The AFOSR fosters and funds basic research within the AFRL, domestic universities, and industry laboratories to support USAF needs. Research managers seek to create revolutionary scientific breakthroughs, enabling the Air Force and industry to produce world-class, militarily significant, and commercially valuable products using technical guidance from the AFRL and requirements of the Air Force; research managers also ensure the transition of research results to support USAF needs.

The Materials and Manufacturing Directorate performs comprehensive research and development activities to provide the Air Force with new and improved materials, processes, and manufacturing technologies. Its activities span 6.1, 6.2, and 6.3. The directorate receives 6.1 funds from the AFOSR for intramural research and has its own 6.2 and 6.3 budget elements for materials R&D and manufacturing technology. The directorate explores new materials, processes, and manufacturing technologies for use in aerospace applications, including aircraft, spacecraft, missiles, rockets, and ground-based systems, along with their structural, electronic, and optical components. Areas of expertise in this directorate include thermal protection materials, metallic and nonmetallic structural materials, nondestructive inspection, materials used in aerospace propulsion systems, electromagnetic and electronic materials, and laser-hardened materials. The directorate provides real-time materials operating problem solutions and failure analysis, along with support to Air Force weapons system acquisition offices and maintenance depots, to solve materials-related concerns and problems. The directorate plans, executes, and integrates advanced manufacturing technology programs and affordability initiatives that address manufacturing process technologies, computer-integrated manufacturing, and excellence through design for producibility, quality, cost, and the use of commercial processes and practices for military needs. The Air Expeditionary Forces Technologies Division, located at Tyndall Air Force Base (AFB), Florida, addresses environmental issues and provides materials expertise for airbase assets such as runways and infrastructure. The directorate also manages the Air Force Corrosion Control Program Office at Robins AFB, Georgia; the Air Force

Nondestructive Inspection Office at Tinker AFB, Oklahoma; and the Air Force Advanced Composites Office at Hill AFB, Utah.

The Propulsion and Power Directorate provides a complete spectrum of advanced propulsion technologies for the nation's military services. The directorate has its own 6.2 and 6.3 budget elements. Its 6.3 funds are the principal source of funding for transitioning new materials to promote application of these technologies to military systems for an aerospace force for advanced aircraft, weapons, and space electrical power system technologies and to advance concepts for advanced air-breathing, rocket, and space propulsion. In addition, the directorate designs and analyzes advanced propulsion concepts and promotes the application of advanced propulsion science and technology to military and commercial systems; assists operational commands and air logistics centers in resolving field problems; and coordinates and participates in joint propulsion science and technology programs with other Air Force Materiel Command, USAF, and Department of Defense (DOD) organizations, NASA, other government agencies, other countries, industry, and academia.[2]

The following sections describe the current and planned approaches and activities of the major contributors addressing Air Force needs in the materials area.

3.2.1 Research Funding and Directions at AFRL

The Air Force Research Laboratory exists to eliminate gaps in technology in order to address today's needs and to reshape tomorrow's Air Force. The longer-term focus is on the future needs of the Air Force.

The AFRL consists of 10 technical directorates, including the AFOSR:

- AFOSR, located in Arlington, Virginia;
- Air Vehicles Directorate, at Wright-Patterson AFB, Ohio;
- Directed Energy Directorate, at Kirtland AFB, New Mexico;
- Human Effectiveness Directorate, at Wright-Patterson AFB, Ohio;
- Information Directorate, at the Rome Research Site, New York;
- Materials and Manufacturing Directorate, at Wright-Patterson AFB, Ohio, and Tyndall AFB, Florida;
- Munitions Directorate, at Eglin AFB, Florida;
- Propulsion and Power Directorate, at Wright-Patterson AFB, Ohio, and Edwards AFB, California;
- Sensors Directorate, at Wright-Patterson AFB, Ohio; and
- Space Vehicles Directorate, at Kirtland AFB, New Mexico;

2 See http://www.wpafb.af.mil/afrl/rz/. Accessed September 11, 2009.

Funding of the directorates is divided between short- and long-term needs, with the emphasis on the long term: 80 percent of funding is for long-term activities.[3] The AFRL responds to the immediate needs of the warfighter by moving staff around as needed to solve short-term issues.

Funding priorities and levels have changed over the years with the changes in the geopolitical world, the economy, and the mission and vision for the AFRL. For example, engineering funding for USAF was cut by approximately 70 percent in the late 1980s and by a further 20 percent in the early 1990s, resulting in a considerable loss of capabilities. The AFRL directorates have not been subject to the same level of engineering reductions as other Air Force functions;[4] however, these reductions have resulted in some increased workloads within the laboratories, as the product centers in the Air Force now look to the AFRL or to the engine contractors or suppliers for solutions.

Research and development at the AFRL is organized in Focused Long Term Challenges (FLTCs),[5] described in Chapter 2 of this report, and 70 to 75 percent of the funding is for tasks held within the FLTCs. The remainder of the funding at the laboratories is for "discovery," or low technology readiness level, less-directed work aimed at longer-term issues. Discovery does include 6.1, low 6.2, and some engineering research.

Discovery includes the 6.1 funding received from the AFOSR; generally, approximately 20 percent of AFOSR's funding goes to the AFRL and constitutes approximately 50 percent of the discovery budget.[6] Most of the remainder of the discovery budget is early 6.2 funding and comes from the directorate budgets. The splits and focus of the discovery money vary by directorate and are set by the priorities of the directorate. In addition to the above sources, there is a special Laboratory Director's fund of approximately $1 million per year. There is an open competition throughout the AFRL for grassroots ideas, with awards of between approximately $50,000 and $100,000 per year for selected projects.

Technology pull comes from the FLTC roadmaps and associated plans. Technology push comes mainly from the discovery activities and Laboratory Director's funding; an example is the modeling of materials and materials behavior that is being explored with discovery funding.

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[3] Information presented to the committee by J. Arnold, K. Stevens, Col. W. Hack, C. Stevens, and C. Ward at Wright-Patterson AFB, May 27, 2009.

[4] Information received during presentations to the committee at Wright-Patterson AFB, Ohio, May 27, 2009.

[5] The committee recognizes that the Materials and Manufacturing Directorate's approach to FLTCs is evolving and dynamic at this time and that some changes in the approach are forthcoming.

[6] Information received during presentations to the committee at Wright-Patterson AFB, Ohio, May 27, 2009.

The FLTCs are divided into near-, mid-, and far-term research and development. The customers and technology providers are intertwined in defining the FLTC goals. Management is done by a matrix method, with each FLTC being assigned to a directorate, which pulls in expertise from other relevant directorates to flesh out priorities and build roadmaps. A single directorate may thus support six to eight FLTCs. Materials, especially high-temperature materials, are important in a number of the FLTCs, and the Materials and Manufacturing Directorate is involved with nearly all of the FLTCs to some degree. The Materials and Manufacturing Directorate has management responsibility for the sustainment FLTC. The sustainment FLTC has a focus on long-term operation and evolutionary progress.[7]

The Materials and Manufacturing and the Propulsion and Power Directorates work quite closely together on common interests. The use of a joint workshop to set the priorities and provide input to the roadmaps is discussed elsewhere in this report. One of the materials and propulsion workshop sessions led to approximately 25 new ideas for materials. Some priority was given to these ideas, and efforts have been made to obtain the required funding.

Each FLTC may have many roadmaps for individual elements of the particular challenge. Roadmaps have "owners" and often include unfunded programs; however, nothing can be added or subtracted without the permission of the owner. These unfunded lines are for technology developments that are identified as being necessary to meet long-term goals but for which there is no funding identified. In general, the FLTCs are ambitious and are underfunded, although they provide a driving force and an interdependent, long-term plan. FLTCs are reviewed regularly and changed as appropriate. Recently, the AFRL has been presenting the FLTCs to industry groups to educate them and to identify areas for collaboration.

There is a balance in research efforts between the AFRL and industry. The situation has changed over the years, with the large prime contractors becoming increasingly more reliant on the suppliers to do research and development. The prime contractors act as integrators, passing some of the materials development work to their suppliers, which puts financial stress on the supplier. Often the result is that incremental changes are possible but revolutionary changes are difficult.

The importance for a project of reaching Milestone B or TRL 6 needs to be emphasized. The milestone is difficult to define exactly, but the focus is on the demonstration of process maturity and component development. Milestone B generally marks the end of 6.3 programs, which start at TRL 4 or 5. The engineering acquisition major review at Milestone B is aimed at managing risk for future development; the effect of this setup is that materials must be selected early in the

[7] As noted above, the committee recognizes that the Materials and Manufacturing Directorate's approach to FLTCs is evolving and dynamic at this time and that some changes in the approach are forthcoming.

process, because the use of new materials may require new designs and increase risk later in the process. Further discussion of risk and the associated valley of death is presented in Chapters 2, 4, and 5, but these topics are mentioned here as they are integral to the FLTC and planning process.

3.2.2 Air Force Office of Scientific Research

Basic research investments for USAF are managed by the AFOSR. As a part of the AFRL, AFOSR's technical experts foster and fund research within the AFRL, universities, and industry laboratories to ensure the transition of research results to support USAF needs. Following are five general focus areas:

1. Aero-structure interactions and control;
2. Energy, power, and propulsion;
3. Complex materials and structures;
4. Space architecture and protection; and
5. Thermal control.

The current AFOSR basic research program is divided into three directorates. Research on aerospace propulsion materials is funded primarily through the Aerospace, Chemical, and Materials Science Directorate under 12 topical areas.[8] The area most relevant to propulsion systems is topical area (7): High Temperature Aerospace Materials (HTAM). As stated in an Air Force BAA, "The objective of basic research in HTAM is to provide the fundamental knowledge required to enable revolutionary advances in future Air Force technologies through the discovery and characterization of high-temperature materials (nominally temperatures above 1000°C), including ceramics, metals, [and] hybrid systems including composites."

Current research under HTAM includes fundamental research on high-temperature materials, focused on understanding combined mechanical behaviors such as strength and toughness as a function of thermal and acoustic loads. For example, the program includes exploratory research on refractory materials systems such as molybdenum and niobium silicides, borides, and boro-silicides that includes studies of phase equilibria, thermal stability, coating methodology, oxidation, corrosion, and mechanical behavior. These types of programs represent long-term, high-risk investments in the development of revolutionary high-temperature materials for propulsion, which are likely to lead to "revolutionary" as opposed to "incremental" advances in the temperature limits of engine operation.

Although the AFOSR has a broad portfolio that is relevant to future propulsion needs, further analysis of the AFOSR portfolio could be useful in order to

[8] See http://www.wpafb.af.mil/AFRL/afosr/. Accessed May 6, 2009.

determine its topical breakdown with respect to the development of new materials at the lower TRLs and how to best coordinate activities with the Materials and Manufacturing and the Propulsion and Power Directorates and obtain inputs from the warfighter. The analysis could consider whether the research portfolio is sufficiently broad to build the desired knowledge base and to train the number of future scientists and engineers needed to address the challenges that lie ahead. In addition, the further analysis should consider the internal investment in materials research through the AFRL and potential interactions with efforts funded by other agencies such as the Office of Naval Research (ONR) and NASA.

3.2.3 Materials Lab: Materials and Manufacturing Directorate

The Materials and Manufacturing Directorate, or the Materials Lab as it is often called, is one of the AFRL's 10 directorates. It performs comprehensive research and development activities to provide new or improved materials, processes, and manufacturing technologies for USAF. The directorate integrates industry requirements with an execution program providing advanced manufacturing processes, techniques, and systems for the timely, reliable, high-quality, economical production and sustainment of Air Force systems. The directorate's areas of expertise include thermal protection materials, metallic and nonmetallic structural materials, nondestructive inspection, materials for aerospace propulsion systems, electromagnetic and electronic materials, and laser-hardened materials. Figure 3.2 presents the directorate's organizational chart.

The directorate addresses the sustained need for metals development currently and into the future, through the Metals Branch of the Metals, Ceramics and NDE [Nondestructive Evaluation] Division. The primary focus of the research is on high-temperature metals; it is aimed at service temperatures in the range from 650°C to 1500°C. The most general objective of the Metals Branch is to establish and maintain leadership in metals technologies for Air Force systems. For the foreseeable future, the group is focused on research in the following areas:

- Materials damage prediction for turbine engine materials,
- Computational tool development,
- Advanced turbine disk materials, and
- Thin gage/honeycomb structure for thermal protection systems.

The objective of the Metals Branch is to understand, develop, and transition metallic materials with high specific strength and stiffness along with other functional properties for use in existing, advanced, and conceptual aerospace systems for USAF. The technical program is implemented through an integrated extramural and intramural program. The extramural program is conducted through contrac-

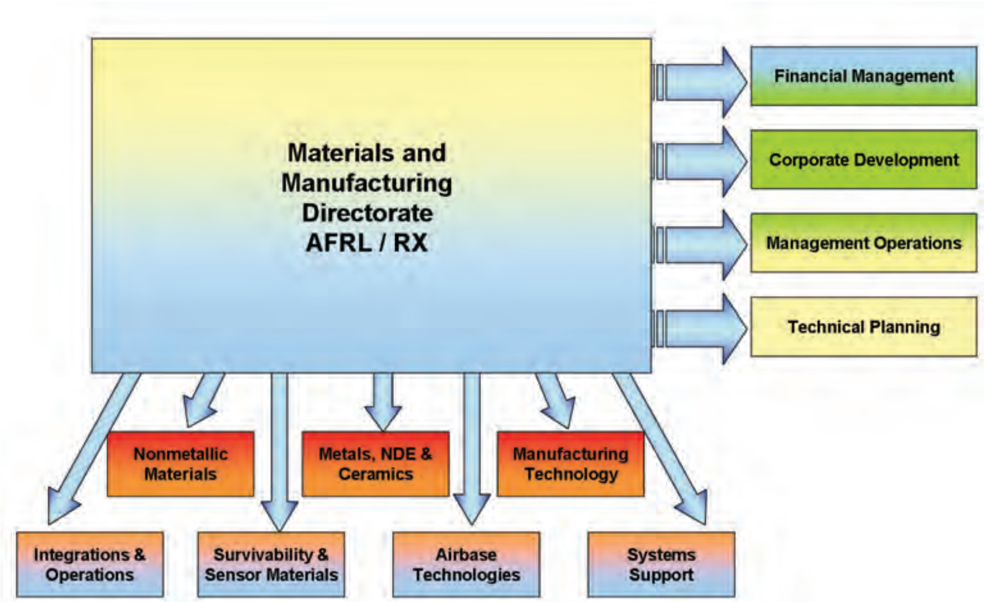

FIGURE 3.2 Organizational chart of the Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/RX). SOURCE: From http://www.ml.afrl.af.mil/orgchart.html.

tual arrangements with aerospace companies and academic institutions. The intramural program is conducted in the facilities of the Materials and Manufacturing Directorate. Technical collaborations with other organizations in the United States and abroad are also pursued. The technical program consists of efforts in four areas: materials damage prediction for turbine engine materials, computational tool development, advanced turbine disk materials, and thin gage/honeycomb structure for thermal protection systems.

The Materials and Manufacturing Directorate receives some 6.1 funds from the AFOSR for intramural research. Within the directorate's own 6.2 and 6.3 budget elements, its scientists and engineers explore new materials, processes, and manufacturing technologies. With a host of modern material analysis laboratories, the directorate performs research on thermal protection materials, metallic and nonmetallic structural materials, nondestructive inspection, materials used in aerospace propulsion systems, electromagnetic and electronic materials, and laser-hardened materials. It also provides real-time operating problem solutions and failure analysis, along with support to Air Force weapons system acquisition offices and maintenance depots, including work on advanced manufacturing technology programs and affordability initiatives. Materials Lab activities address environmental issues, and lab activities through the Air Expeditionary Forces Technologies

Division, located at Tyndall AFB, Florida, provide materials expertise for air base assets such as runways. The Materials Lab also manages the Air Force Corrosion Control Program Office at Robins AFB, Georgia; the Air Force Nondestructive Inspection Office at Tinker AFB, Oklahoma; and the Air Force Advanced Composites Office at Hill AFB, Utah.

The historic model described in Figure 3.1 continues to frame the current approach for Air Force propulsion materials development.[9] Several organizational and programmatic changes over the past few years have changed the materials development environment, resulting in changes in this decade compared with the previous several decades. These changes include a significant reduction in applied research in other agencies working on propulsion materials technology, and a contract focus for the materials work on the Integrated High Performance Turbine Engine Technology (IHPTET) Program (and the Versatile Affordable Advanced Turbine Engine [VAATE] Program that has replaced it).[10] Also, the level of funding available for propulsion has been reduced as a result of a diffusion of focus due to the increased diversity of the Air Force mission(s) in recent years.[11]

The historic model has also been modified to some extent on the contractor's side in recent years. The current business model gives suppliers more responsibility for component manufacturing process development and more involvement in the details of the design. Several of the engine manufacturers have reported a deterioration in some of the supplier base with respect to addressing propulsion materials as the pressures for more short-term profitability have increased in the supplier base.[12] The propulsion industry has undergone some restructuring in recent years that has had an effect on materials development in the United States. Pratt and Whitney has consolidated its material activities from its Florida R&D facility into the East Hartford, Connecticut, operation,[13] resulting in a reduction of the total number of materials scientists and engineers. The Rolls-Royce acquisition of Allison Engine Company generated the Liberty Works that is focused exclusively on military technology, while Honeywell has purchased the parent company of Allied Signal Propulsion. The committee could not make an assessment of the impact of these changes relative to meeting U.S. military needs, although the changes are significant enough to be noted here.

[9] J. Arnold, K. Stevens, Col. W. Hack, C. Stevens, and C. Ward, Wright-Patterson AFB, presentations to the committee, May 27, 2009.

[10] Chart: "Funding History for Propulsion Materials: (6.2) Funding—Applied Research," C. Ward, presentation to the committee, Irvine California, January 29, 2009.

[11] National Research Council. 2006. *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs*. Washington, D.C.: The National Academies Press.

[12] Malcolm Thomas, Rolls-Royce North America; Frank Preli, Pratt and Whitney; Art Temmesfeld, Air Force Research Laboratory; presentations to the committee, Washington, D.C., March 23, 2009.

[13] Jack Schirra, Pratt and Whitney, briefing to the committee, Washington, D.C., July 20, 2009.

Another factor affecting the overall level of materials R&D is the reduced number of new weapons systems in development along with the reduced quantity of buys and the reduced number of competitive 6.3 demonstrators, as also noted in Chapter 2. The reduced number of new propulsion systems in development does not directly dictate that there will be a reduced new materials development effort, since history has shown materials advances to be a significant contributor to upgrades for current systems and an important factor in maintaining a U.S. competitive edge in weapons system capabilities.[14] The reduction in the number of technology demonstrators in the IHPTET historical model, which had three large competing demonstrators, to the current level in the VAATE Program has reduced the opportunity to bring new talent into the field. These reductions are directly related to the quantity of the investment available for materials-related R&D. These reductions have a dual effect on the production of materials advances: they lead to fewer and less diversified ideas and approaches being pursued and to a loss of the competitive atmosphere among contractors. Compounding this effect is the reduced investment in new materials through Materials and Manufacturing Directorate research found in these demonstrators.[15]

Other issues that were raised during the committee's visit to Wright-Patterson AFB on May 27, 2009, included a reduced emphasis on traditional propulsion materials technology at the level of the Director, Defense Research and Engineering (DDR&E), compared to the support for the area in the 1980s and 1990s; the reduced emphasis is due to the increase in missions to which the Office of the Secretary of Defense (OSD) is responding to today. This reduced emphasis is reflected in the projected 6.2 funding levels for future propulsion programs as shown in the National Research Council report *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs.*[16] Also, some concern was expressed by AFRL personnel that the 6.1 research work supported by the AFOSR was not as closely linked to the propulsion needs as it had been in the past. It was noted by the committee during the May visit that this work needed to be more far-term and that it should not be too closely linked to requirements, but needs to be free to deal with more creative advances in materials science and engineering. It was pointed out during the visit that several of the major materials advances (e.g., gamma titanium aluminides) were the direct results of competition among contractors (Pratt and Whitney, GE, and Allison) and that the recent action that narrowed

[14] National Research Council. 2006. *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs.* Washington, D.C.: The National Academies Press.

[15] J. Arnold, K. Stevens, Col. W. Hack, C. Stevens, and C. Ward, presentations to the committee, Wright-Patterson AFB, Ohio, May 27, 2009.

[16] National Research Council. 2006. *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs.* Washington, D.C.: The National Academies Press.

VAATE-type technology demonstrators down to a single contractor demonstrator will significantly diminish competition-driven advancements.

During their visit to Wright-Patterson AFB in May 2009, committee members were presented with an overview of the integrated planning process that involves each of the AFRL lab directors being assigned to lead one of eight Focused Long Term Challenge areas (e.g., the director of the Materials and Manufacturing Directorate is responsible for the sustainability area). These challenge area teams are staffed with cross-functional personnel from other directorates who help make the directors and members aware of USAF challenges. The teams also include members from the AFRL planning group who are responsible for structuring the planning and budgeting document for the entire AFRL. The directors of the Materials and Manufacturing and the Propulsion and Power Directorates had recently organized a Propulsion Materials Workshop that resulted in signs of improved communications and coordination between the two directorates. The committee views this as a very positive move, but observed that there was not representation from the AFOSR, the user commands, or the systems program offices and that these workshops were not institutionalized as regularly scheduled events.

3.3 MATERIALS RESEARCH AND DATABASES

3.3.1 Basic Research

Fundamental research supported by the AFOSR is not tied to specific platforms or systems but is designed to build a knowledge base that may be relevant to desired long-term capabilities (i.e., 20 to 30 years in the future). As stated in Chapter 2, the current AFOSR broad agency announcement[17] describes research opportunities that are consistent with the capability-based planning approach. Research related to materials for propulsion applications is described in several of the programs within the research portfolio, including the High Temperature Aerospace Materials Program.

The HTAM Program[18] clearly identifies both air-breathing and rocket propulsion systems as application areas of interest. The program emphasizes several aspects of materials research, including the discovery of new materials with superior performance above 1000°C, microstructural evolution at elevated temperatures, and materials behavior under combined loadings (e.g., mechanical and acoustic).

Potential propulsion applications addressed by the HTAM Program are shown in Figure 3.3. Technology areas either funded currently or over the past 10 years

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[17] See AFOSR BAA-2008-1. Available at http://www.wpafb.af.mil/AFRL/afosr/. Accessed March 8, 2009.

[18] Document AFD-080612-188.

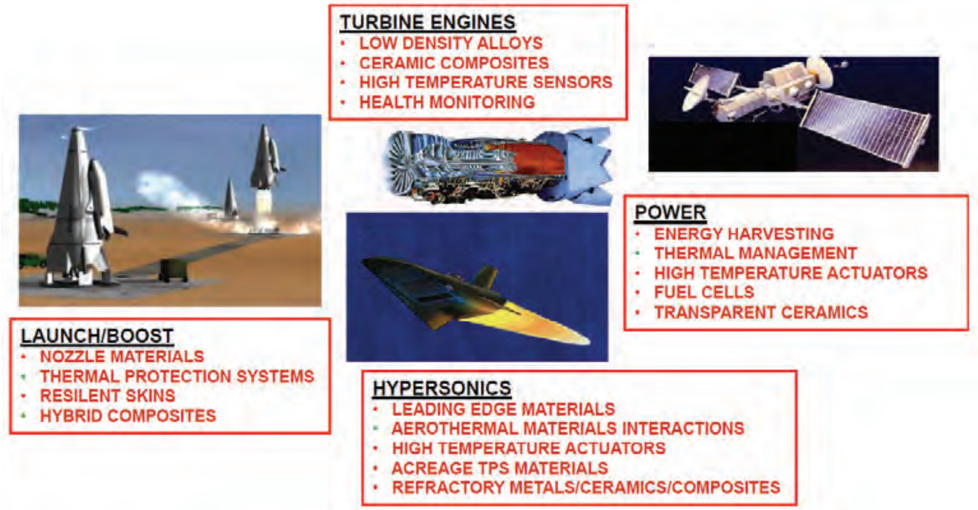

FIGURE 3.3 Description of future applications and the impact of high-temperature materials. SOURCE: Reprinted from Document AFD-080612-188, available at http://www.wpafb.af.mil/shared/media/document/AFD-080612-188.pdf.

for metals and ceramics research show an emphasis on materials for engines and nozzles (more than 80 percent) with some funding also directed toward skins. The HTAM Program appears to be well aligned with the needs for future propulsion systems. The Polymer-Matrix Composites Program focuses on the use of polymer-matrix and carbon-fiber-reinforced materials and appears to be aligned to directly address future needs that are related to propulsion systems. The program encourages both experimental studies and computational approaches for matrix resins, fibers, plies, and laminates. The use of multiscale modeling is a specific area of interest.

Although the AFOSR has a broad portfolio that is relevant to future propulsion needs, further analysis needs to be conducted to determine if the amount of the current investment is appropriate. The analysis should consider whether the research portfolio is sufficiently broad to build the desired knowledge base and to train the number of future scientists and engineers needed to address the challenges that lie ahead. In addition, the further analysis should consider the internal investment in materials research through the AFRL and potential interactions with efforts funded by other agencies such as the ONR and NASA.

Complementing the AFOSR materials science activities and coordinated with these activities is the work at the Office of Naval Research. Relevant to the committee's statement of task (see Appendix A) are the ONR initiatives that support university-based research related to aerospace propulsion. The ONR S&T program generally supports basic and applied research and advanced development in the physical sciences and engineering, materials and processing, and environmental quality that enable enhanced performance, affordability, and reliability for future and legacy Navy and Marine Corps systems and platforms.

The Sea Warfare and Weapons Department (Dept. 33), under the Code 332 High Temperature Materials Program, has continuous thrusts to develop higher-temperature materials to meet future naval challenges and capability requirements for future aircraft and shipboard gas turbine engines, hypersonic vehicles, and critical missile components.[19] Reliable high-temperature materials are also needed to improve engine efficiency and decrease maintenance costs. Much of the work supported under this topic is currently focused on the development of thermal barrier coatings (TBCs) for turbine-engine applications. Efforts in this area concentrate on thermal stability, high-temperature phase equilibria, bond coating materials (e.g., platinum intermetallics), degradation of coatings by stress and corrosion, environmental contamination, delimitation, rumpling, and other mechanisms. Some work on new materials such as refractory silicides and borides is also supported.

The current ONR effort seems to be reasonably well coordinated with the AFOSR effort, with a division of tasks to avoid redundancy. The ONR effort supports the broader mission to develop advanced materials for aerospace propulsion, but it is rather focused and quite limited in scope. Once again, further analysis is recommended to determine whether the amount and breadth of this work are adequate to meet future military needs and to ensure that the U.S. military is at the forefront in the development of revolutionary propulsion technology. As with the case of the AFOSR, the training of future scientists and engineers in this critical technology area should be a key consideration in this analysis.

Other government agencies that provide broad-support basic research in high-temperature aerospace materials include the U.S. Department of Energy (DOE) through its High Temperature Materials Laboratory (HTML) at the Oak Ridge National Laboratory (ORNL). The HTML is a national user facility designed to support the development of advanced materials. It is sponsored by the DOE Office of Transportation Technologies in the Office of Energy Efficiency and Renewable Energy.

Through HTML, researchers from U.S. industries, universities, and government agencies have access to hands-on assistance from a skilled staff and to a number of sophisticated, often one-of-a-kind, instruments or facilities for materials characterization. The 64,500-square-foot building houses six user centers, which are clusters of specialized equipment designed for specific types of property measurements. The HTML also has a neutron beam-line facility at the high flux

[19] David Schifler, ONR, briefing to the committee, Washington, D.C., July 20, 2009.

isotope reactor (HFIR) at the ORNL and a synchrotron beam line at the National Synchrotron Light Source at the Brookhaven National Laboratory.

This type of user center provides access for university groups to a broad range of facilities for the characterization of structure, phase equilibria, thermochemistry, and mechanical properties of materials at elevated temperatures. This critical resource provides university research with unique tools and facilities to support high-temperature materials development.

The extreme temperature and environmental stability requirements posed by aerospace propulsion systems and the substantial technological payoff for materials improvements have acted as a strong "pull" and have provided much of the driving force for fundamental research on high-temperature metals, alloys, ceramics, and composites. The scientific knowledge base that underlies the development of advanced aerospace propulsion materials is highly multidisciplinary. Heat transport, atomic transport, high-temperature corrosion and oxidation, deformation, fracture, and fatigue are among the complex phenomena involved in the performance of high-temperature materials in the extreme environment of turbine engines and rocket propulsion systems. Current state-of-the-art incumbent materials, their processing and manufacturing technologies, and the engineering know-how surrounding these materials were not developed for their own sake, but rather to meet the needs created by advancing propulsion systems; they are the result of decades of materials research and practical engineering experience.

To meet the materials needs and requirements for the next generation of advanced propulsion systems requires highly skilled scientists, mostly at the PhD level, trained in disciplines mentioned above, as well as a pipeline of evolving materials solutions and strategies to enhance the present capabilities.

Fundamental research is needed; however, investing in a broad portfolio is not enough. Mechanisms are needed by which promising results can be selected for the further support of more applied research and/or development to bridge the so-called valley of death between academic research and real-world applications. (Further discussion of risk and the associated valley of death is presented in Chapters 2 and 4.)

The committee reviewed the relationship between AFOSR interactions with the Materials and Manufacturing Directorate in implementing this transition of the technology and concluded that additional coordination would significantly improve the process of recognizing material transition opportunities and accelerating these to higher TRLs.

3.3.2 Applied Research and Materials Demonstrations and Development

As discussed in detail above, the time and effort required to introduce a new conventional (Ti-, Ni-, Co-, or Fe-based) alloy into aircraft engines typically take approximately 5 to 20 years. Precise timing depends on the degree of departure that the new alloy represents from the current alloy and the availability of significant industrial-base manufacturing capabilities, as well as on whether an application window of opportunity exists. Established design practices, materials and process understanding, and industrial procedures are the results of experience gained in successfully designing, using, and producing materials. New alloys represent an opportunity to learn what portions of established practices are no longer applicable to the new material. Since all materials have their advantages and disadvantages, the convergence of design practices and materials and processing knowledge is a fundamental requirement for the successful engineering application of materials.

As shown in Table 3.1, the Air Force funding planning line for Materials for Structures, Propulsion, and Subsystems submitted to Congress to support this type of work shows a reduction from the fiscal year (FY) 2007 level to the FY 2008 level; in future years there might be an increase. The committee recognizes that the final funds appropriated by the congressional process may differ from the amount requested, since it has been common for Congress to add funds for earmarked programs that are not in the focused R&D plan; however, the committee understands that Table 3.1 represents Air Force planning for Materials for Structures, Propulsion, and Subsystems.

Large-scale component or rig tests and engine demonstrators have been an important part of the historical U.S. material development process (6.1, 6.2, and 6.3 funding) and transition to use in propulsion systems.[20] While the Air Force lead military demonstrator programs have been the most productive, it is appropriate in the context of the statement of task for this report to recognize that the NASA High Speed Civil Transport Program and several other NASA programs have made significant contributions to U.S. applied materials research and development. Included in these developments are contributions to the advancement of superalloy turbine disk materials, thermal barrier coatings, single-crystal blade alloys, gamma TiAl, and ceramic-matrix composites for combustion liners, discussed in Chapter 2.

The close linkage of military applied materials development and demonstrator programs dates back to the Advanced Turbine Engine Gas Generator programs of the 1970s. The linkage became more focused under the DOD coordinated Integrated High Performance Turbine Engine Technology Program that ran from 1988 through 2005. This program had clear technology goals without being tied to a specific mission. In the IHPTET Program, materials advances were considered necessary to meeting the goals and were an integral part of the effort, with funding as part of the demonstrator programs. This program produced significant advances

[20] Chuck Ward, AFRL, "Materials Needs and R&D Strategy for Future Military Aerospace Propulsion," presentation to the committee, Washington, D.C., January 29, 2009.

TABLE 3.1 U.S. Air Force Propulsion-Related Materials Budget Items: Actual (FY 2007 and FY 2008) and Estimated (FY 2009 and FY 2010) (in US$ millions)

	FY 2007 Actual Cost	FY 2008 Actual Cost	FY 2009 Estimated Cost	FY 2010 Estimated Cost
Total program element	151,438	175,040	188,152	127,957
6201SP: Space Materials Development	25,728	36,012	28,963	0.000
624347: Materials for Structures, Propulsion, and Subsystems	70,723	65,942	83,446	82,625
624348: Materials for Electronics, Optics, and Survivability	26,687	26,068	35,703	27,087
624349: Materials for Technology for Sustainment	21,550	28,912	29,223	14,312
624915: Deployed Air Base Technology	6,750	18,106	10,817	3,933

SOURCE: Propulsion-Related Materials Budget, PB 2010 Air Force RDT&E Budget Item Justification, May 2009, PE 0602102F Materials, 3600-Research, Development, Test and Evaluation, Air Force/BA2—Applied Research.

in the areas of wrought gamma TiAl, SiC/SiC ceramic-matrix composites, high cycle fatigue, and titanium- and organic-matrix composites.

The Versatile Affordable Advanced Turbine Engine Program was initiated in 2005 as a follow-on to the IHPTET Program[21] and is scheduled to run through 2017. The program has strong ties to mission goals and an acknowledgment of material needs. However, traditional materials research was excluded from the program due to concern about schedule risks. Some company proprietary work was included as competitive positioning by the contractors. Advanced materials demonstrations based on work from previous programs include advanced nickel disk alloys, the application of material-behavior-and-life-prediction methods, and ceramic and ceramic-matrix composite materials. The two demonstration components of VAATE are the Advanced Versatile Engine Technology (ADVENT) Program, with a goal of reaching TRL 6 in 2012, and the Highly Efficient Embedded Turbine Engine (HEETE) Program, with a goal of TRL 6 by 2016. The original plan for HEETE includes some materials R&D, but only in the last phase and only with a very limited insertion plan.

Since initiation of the VAATE Program, the Materials and Manufacturing and the Propulsion and Power Directorates have held a series of workshops to better define the materials requirements for the range of propulsion options defined by the Air Force as a result of the FLTC planning. An example of this planning is

[21] Charles W. Stevens, AFRL, "Versatile Affordable Advanced Turbine Engine Program," presentation to the committee, Washington, D.C., March 29, 2009.

summarized in the International Traffic in Arms Regulations (ITAR)-controlled report provided to the committee.[22] It appears that that report has served to define key materials R&D activities that will, with appropriate funding, leverage future propulsion capabilities. It also appears that this planning was specifically directed toward trying to make the normal annual funding in the Materials and Manufacturing Directorate available for developing some material to put into the HEETE engine, as discussed below.

3.3.3 Current and Planned Demonstrator Engine Programs

The funds recently awarded to the ADVENT Program will result in a TRL 6 engine-demonstration project by 2012. Owing to time constraints, ADVENT will only use materials that have already been demonstrated in a component or rig test—that is, materials must have reached TRL 5 prior to being used in the ADVENT demonstrator engine. This type of engine-demonstration program is important to furthering the use of advanced materials in future propulsion systems; however, it does not provide an opportunity to develop new or even improved materials. The HEETE Program plan is currently aligned with the materials development plan and will provide transition opportunities for new materials, provided that they have reached sufficient maturity, TRL 4 or 5, by the time they are transitioned.

The VAATE Program is a collaborative effort in which the DOD community, NASA, and the DOE and the major engine manufacturers and weapon system contractors come together under the auspices of the OSD to share knowledge of their individually funded efforts related to gas turbine engine technology. It is a mechanism for cooperation and potential collaboration, not a "program" in the sense of a single funded entity.

The AFRL Materials and Manufacturing Directorate and the ONR have participated in the VAATE Program since its inception, and both organizations have funded materials development efforts at the engine manufacturers that advance the state of the art of turbine engine materials. Traditionally, the AFRL Propulsion and Power Directorate has also funded 6.3 materials-related efforts as an integral part of engine-demonstrator programs.

From a materials perspective, such efforts are narrowly focused on making components for a given engine and in some cases are best regarded as "technology pushes" rather than as steps for the orderly insertion of a new material. While such efforts may increase the TRL of a material, they do little to advance the manufacturing readiness level (MRL); so while an engine demonstration incorporating a

[22] Air Force Research Laboratory. 2008. *Materials for Advanced Aerospace Propulsion and Power Systems*, AFRL-RZ-WP-TM-2008-2127, October.

new material shows the material to have a capability (i.e., because of high-enough TRL), it may not be ready for insertion into a new or a legacy engine system because of the inability to produce the material on a sustainable scale. For example, a proper manufacturing base may not be available—the component was probably manufactured once in a model shop environment. Recall the following:

- TRLs provide a common language and widely understood standard for
  - Assessing the *performance maturity* of a technology and plans for its future maturation, and
  - Understanding the level of *performance risk* in trying to transition the technology into a weapon system application,
- Whereas MRLs provide a common language and standard for
  - Assessing the *manufacturing maturity* of a technology or product and plans for its future maturation, and
  - Understanding the level of *manufacturing risk* in trying to produce a weapon system or transition the technology into a weapon system application.

TRL 1 through 6 and MRL 1 through 6 are related, whereas MRL 7 and 8 are seen as comparable with TRL 7, MRL with TRL 8, and MRL 10 with TRL 9.[23]

In addition, developmental engine tests are not planned to demonstrate the full-life performance of components, leaving the question of the long-term durability of materials in an aggressive environment unanswered.

Current materials development within the Air Force and the engine manufacturers as assessed by the Materials and Manufacturing Directorate is categorized in Table 3.2, including the 6.3 type of demonstrations noted above. It should be said that a portion of detailed materials work by the engine manufacturers is considered proprietary, and it is difficult to determine the depth of the efforts.

3.3.4 Materials Database Availability

The global engine producers generate a significant quantity of materials property data in support of materials development and insertion, in accordance with military customer and civil certification agency requirements. Wider access to materials property data for advanced materials would provide property benchmarks for materials developers, enable researchers to develop and validate property models, and eliminate the cost of redundant testing. A widely accessible database of

[23] Art Temmesfeld, Air Force Research Laboratory, "Air Force Manufacturing Technology Program, Propulsion Manufacturing Readiness Assessment and the Advanced Manufacturing Propulsion Initiative," presentation to the committee, Washington, D.C., March 23, 2009.

TABLE 3.2 Assessment by the Air Force Research Laboratory's Materials and Manufacturing Directorate of Current Materials Activities

Materials System	6.1 Type Activity	6.2 Type Activity	6.3 Type Activity
High-temperature organic-matrix composites	AF activity: None Co. activity: None	AF activity: Low Co. activity: Low	AF activity: None Co. activity: Low
Advanced titanium-based alloys	AF activity: Moderate Co. activity: None	AF activity: None Co. activity: Low	AF activity: None Co. activity: Low
Advanced nickel alloys	AF activity: Moderate Co. activity: Low	AF activity: Low Co. Activity:Moderate	AF activity: None Co. activity: Moderate
Refractory alloys	AF activity: Low Co. activity: Low	AF activity: None Co. activity: None	AF activity: None Co. activity: None
Ceramic and ceramic-matrix composite materials	AF activity: Low Co. activity: None	AF activity: Moderate Co. activity: Moderate	AF activity: Low Co. activity: Moderate
Thermal barrier coatings and thermal management	AF activity: None Co. activity: Moderate	AF activity: None Co. activity: Moderate	AF activity: None Co. activity: Moderate
Hybrid disk systems	AF activity: Low Co. activity: None	AF activity: High Co. activity: Moderate	AF activity: Low Co. activity: Low

NOTE: Activity categorization: None, Low, Moderate, and High; AF, Air Force; Co., companies.

SOURCE: Memo from Charles Ward, Air Force Research Laboratory, Materials and Manufacturing Directorate, to Committee on Materials Needs and R&D Strategy for Future Military and Aerospace Propulsion Systems, November 12, 2009.

materials property data similar to that available to other scientific and engineering communities in other areas of research would serve to accelerate materials research and academic training.

Some industry data are available to the materials community at large. For example, data for well-established materials are cataloged in the *Military Handbook,*[24] whereas data from DOD contract reports can be acquired from the Advanced Materials, Manufacturing, and Testing Information Analysis Center. This latter organization is chartered by the DOD to serve as a repository for materials and manufacturing reports as well as to analyze and disseminate technical information for advanced materials.[25] Despite these resources, however, the materials community does not have access to the most important and recent industrial materials property data for advanced propulsion materials.

[24] DOD. 1998. *Military Handbook: Metallic Materials and Elements for Aerospace Structures,* MIL-HDBK-5H.

[25] See http://ammtiac.alionscience.com/about/. Accessed July 7, 2009.

Engine manufacturers have limited incentive to share their extensive property data for these materials, for legal, financial, and competitive reasons, as outlined below:

- Materials data for the most advanced materials generated by the U.S. engine companies are often export-controlled and subject to ITAR (e.g., data for powder metallurgy disk alloys).
- Data on engine life are highly competition-sensitive. Engine manufacturers have a disincentive to convey materials property data to competing manufacturers—particularly creep, fatigue, and hold-time low cycle fatigue (LCF) data that directly relate to calculated component life limits.
- Engine life management depends on materials property data that are relevant to a company's lifing methods and the processing used to produce specific engine hardware. Although material property testing is conducted to American Society for Testing and Materials (ASTM) standards, engine manufacturers often institute additional control to regulate specimen geometry, machining (surface condition and residual stress), and test protocols.
- Shared materials property data from the wider materials community offer limited value to engine manufacturers. Without direct knowledge of material pedigree and control of testing, engine companies subject themselves unnecessarily to legitimate legal liability if data generated by the materials community are proved to be erroneous or inappropriate. Engine makers are fully committed to both flight safety and the financial risk of inappropriate engine warranties.

These legitimate industry concerns need to be balanced against the benefits of data sharing. There appears to be an appropriate level of controlled cooperative programs[26] among engine manufacturers, materials and component suppliers, and external materials scientists that could reduce the cost and time to develop material property data for advanced materials.

3.4 MATERIALS CONTRIBUTION TO CURRENT AND EMERGING PROPULSION SYSTEMS

3.4.1 Turbine Engines

For more than 50 years, materials have been the major enabler for the evolution of aircraft turbine engines. At the very beginning of powered flight, the Wright brothers depended on a revolutionary new material, aluminum, for the

[26] Programs that reflect intellectual property and ITAR concerns.

performance of their engine.[27] Whittle[28] and von Ohain,[29] inventors of jet propulsion, depended on steel for their engines. Today's modern turbine engines depend on high-performance materials such as nickel-based superalloys, thermal barrier coatings, and advanced composites for their exceptional performance.

Engineers have learned over the years that improvements in gas turbine engines require improvements in service temperatures. Increased temperature capability can be achieved through the development of new and improved materials as well as through innovative designs, with both materials and designs dependent on advanced processing techniques. Improved temperature capability allows higher turbine inlet temperatures, resulting in increased thermodynamic efficiency and improved performance.

A key performance figure of merit is the ratio of thrust to weight. Developments in advanced materials have been the major contributor to the unparalleled growth in the thrust-to-weight ratio in gas turbine engines. For example, the substitution of Ti- and Ni-based superalloys for steel was a major evolutionary step. More recently, the introduction of advanced ceramic-matrix composites (CMCs), with their improved specific properties, has resulted in further increases in the thrust-to-weight ratio of low-bypass turbofan engines. Similarly, improvements in specific fuel consumption, also dependent on thermal efficiency, have been realized with the use of advanced materials processes. Within the past decade, the DOD's IHPTET Program for low-bypass turbofan engines has demonstrated thrust-to-weight improvements on the order of 60 percent, to approximately 9:1. A significant portion of this improvement can be attributed to the use of higher-temperature superalloys and CMC materials in the engine hot section and polymeric composites for fan casings. The engine weight reductions arise not only from material density reductions but also from the reduction in core engine size enabled by the higher temperatures. Similarly, a reduction in specific fuel consumption, which is also dependent on improved thermal efficiency, has been realized with the use of advanced materials and processes.

A diagram of a typical turbofan jet engine is shown in Figure 3.4, with the key components identified. As shown in the associated graphs on the figure, temperature and pressure dramatically increase from left to right in the engine, with maximums occurring in the area of the combustion chamber and high-pressure turbine (HPT). Today's engines see temperature extremes from ambient temperature in the front of the engine to values of 1000°C or higher in the HPT. Similarly,

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[27] See http://www.nasm.si.edu/wrightbrothers/fly/1903/engine.cfm. Accessed April 2, 2009.

[28] Frank Whittle. 1981. *Gas Turbine Aero-thermodynamics: With Special Reference to Aircraft Propulsion.* Elmsford, NY: Pergamon.

[29] Jacob Neufeld, George M. Watson, Jr., and David Chenoweth. 1997. *Technology and the Air Force: A Retrospective Assessment.* Darby, Pa.: DIANE Publishing.

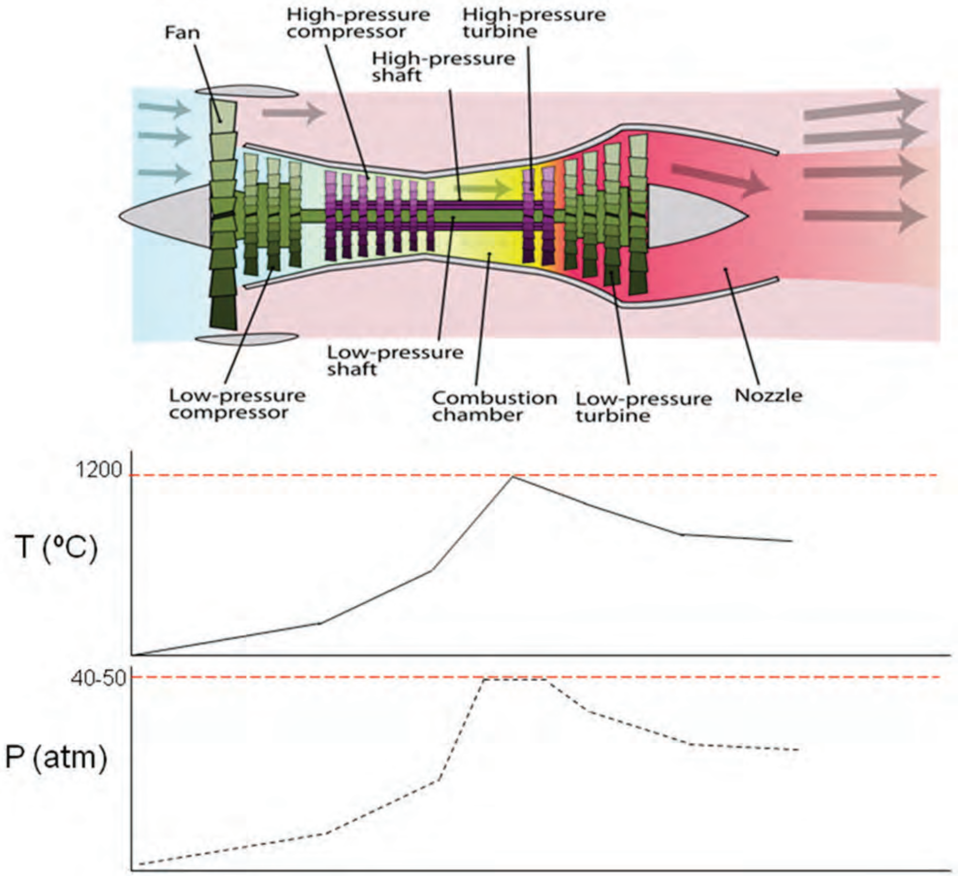


FIGURE 3.4 Cross section of a turbofan engine and the related temperature (T) and pressure (P) values along the engine. SOURCE: Reprinted from "Turbofan" at http://en.wikipedia.org/wiki/File:Turbofan_operation.svg.

pressures can increase to 40 to 50 atm in the HPT. The materials and their associated processes will accordingly change with their location in the engine to provide the necessary thermal stability.

Looking at the materials as a function of location in the engine is a useful approach to showing how materials have contributed to dramatic improvements in propulsion. Three major sections of the engine are considered here: (1) the fan or low-pressure compressor (LPC), (2) the high-pressure compressor (HPC), and (3) the turbine and combustor.

Fan or Low-Pressure Compressor

As shown in Figure 3.4, the fan or LPC section of the engine is cooler and operates at lower pressures than is the case with succeeding sections. For several years, Ti alloys have been the materials of choice for fan blades and cooler sections of the compressor. Use temperatures as high as 350°C to 400°C have been achieved. Replacement of steel by Ti resulted in improved specific properties such as strength and fatigue, which in turn produced improved performance and reliability. Advanced processes (such as diffusion bonding and electron-beam welding) coupled with improved properties of Ti alloys also enabled design changes such as large hollow fan blades and welded construction blisks. In recent years, carbon-fiber-reinforced organic-matrix composites have been used in fan blades, also reducing weight and improving performance.

High-Pressure Compressor

The HPC, as shown in Figure 3.4, is subject to much higher temperatures and pressures than those to which the fan and LPC are subject. Typically, the HPC is where the designers transition to higher-temperature materials. To keep pace with the desire of designers to increase performance, Ti alloys have been improved steadily over the years. For example, alloys such as IMI 834 are useful to temperatures of 600°C to 650°C. As HPC temperatures have increased, Ni-based superalloys have replaced Ti-based alloys in many areas. Even though superalloys result in a weight penalty, they provide higher temperature capability, allowing higher compression ratios and improved performance.

Turbine and Combustor

The turbine and combustor sections of the engine are the hottest, as shown in Figure 3.4, and are historically the domain of Ni-based alloys. The temperature capability of these alloys has progressed steadily over the years, shown in Figure 3.5. The evolution in temperature capability of blades has resulted from improvements in alloy composition and processing, from wrought, to conventionally cast, to directionally solidified, to single-crystal blades. Wrought nickel alloys replaced steel alloys, allowing higher temperature and improved performance. Going to a casting process provided a temperature increase of about 100°C due to the ability to incorporate cooling channels as well as higher creep resistance due to larger grain size. Directional solidification (DS) eliminated transverse grain boundaries, providing another increase in use temperature, once again due to improved creep resistance. Most recently, single-crystal blades eliminated grain boundaries altogether, resulting in improved creep resistance and, in turn, another incremental increase in use tempera-

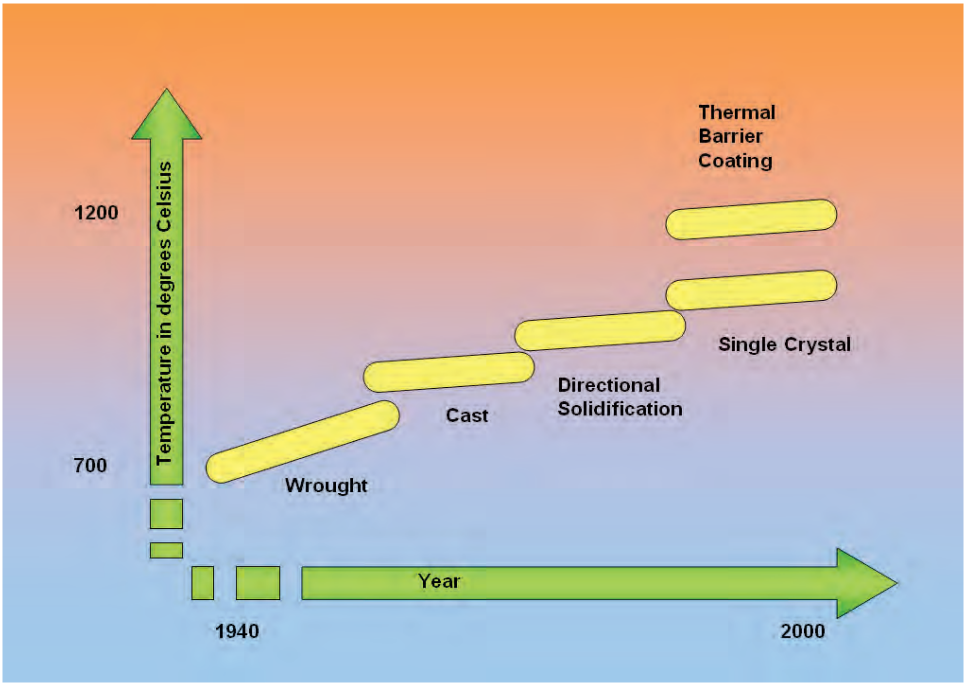


FIGURE 3.5 Increase in operational temperature (T) of turbine components, 1940 to 2000. SOURCE: Data from U. Schulz, C. Leyens, K. Fritscher, M. Peters, B. Saruhan-Brings, O. Lavigne, J. Dorvaux, M. Poulain, R. Mevrel, and M. Caliez. 2003. "Some Recent Trends in Research and Technology of Advanced Thermal Barrier Coatings," *Aerospace Science and Technology* 7:73-80.

ture. Beyond the capabilities afforded by the alloys and their associated processes, the utilization of thermal barrier coatings provided another 100°C or so increase in temperature capability. Yttria-stabilized zirconia and other TBCs reduce the heat transfer from the flame to the substrate. Because of their porosity, TBCs require the use of an oxidation-resistant coating (such as NiAl) between the TBC and the substrate.

Additional critical materials in key components include cobalt alloys in the combustor and high-strength steels in shafts and the use of cast gamma TiAl in low-pressure turbine (LPT) blades. TiAl provides higher specific properties such as high-temperature strength and stiffness, resulting in improvements in such areas as fuel consumption.

Summary and Future Directions for Turbine Engines

The near-term future no doubt promises fewer transition opportunities than were available in the past for the development of new materials or for the improvement of current materials, owing to the military sector's lack of planned new systems and the commercial sector's focus on cost and risk. Where opportunities do appear, thrust-to-weight ratio and specific fuel consumption will continue to be two key measures of advanced engine performance. These will be integrated with the desire to reduce cost throughout the development, application, and sustainment cycle.

3.4.2 Scramjet Engines

Desired future DOD capabilities that include aspects of prompt global strike, extending the vertical limit of the battlefield, and responsive access to space[30] have driven interest in developing flight vehicles capable of sustained flight at Mach 5 or higher (i.e., the hypersonic regime). Hypersonic flight represents a revolutionary advance in capabilities. However, revolutionary advances in the propulsion systems are required to enable this technology. For reusable hypersonic flight vehicles, air-breathing propulsion systems offer the promise of combining high specific impulse (thrust normalized by the amount of fuel burned) with speeds of Mach 5 to 10 or higher.[31] This section focuses on supersonic combustion ramjets, typically shortened to scramjets, as a potential enabling technology for hypersonic propulsion. In the end, scramjets will likely be one component of a combined-cycle propulsion system that includes some other engine (e.g., rocket or turbine-based) to accelerate to the speed at which scramjets can operate efficiently, which is above about Mach 5.

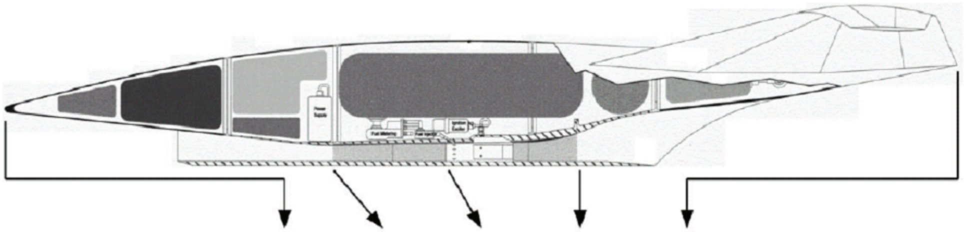
As discussed in the Section 3.4.1, turbine engines have a series of complex, rotating parts such as those used to compress the air used for combustion. In contrast, scramjets use the kinetic energy of the vehicle to compress air as it enters the engine (Figure 3.6). This makes scramjet designs conceptually simple, as shown by the schematic cross section of a hypersonic flight vehicle in Figure 3.6. One of the main challenges in scramjets is the extreme temperatures encountered during operation.[32] Relatively modest speeds by hypersonic standards result in temperatures over 2000°C for the engine inlet cowl, fuel injection areas, and the exit nozzle (Figure 3.7). Possible designs of the hottest areas of the engine require novel materials or approaches to deal with the temperatures and heat loads.

The extreme temperatures associated with scramjet propulsion are beyond the operating regime for materials used in conventional propulsion applications. Using engine cowl inlets as an example, some of the concepts that are being

[30] U.S. Air Force Strategic Plan, available at http://www.airforcestrategynet.mil/. Accessed March 2009.

[31] T.A. Jackson, D.R. Eklund, and A.J. Fink. 2004. "High Speed Propulsion: Performance Advantage of Advanced Materials," *Journal of Materials Science* 39(19):5905-5913.

[32] D.M. Van Wie, D.G. Drewry, Jr., D.E. King, and C.M. Hudson. 2004. "The Hypersonic Environment: Required Operating Conditions and Design Challenges," *Journal of Materials Science* 39(19):5915-5924.



Enigne Station	Free Stream	Inlet Throat	Combustor Entrance	Combustor Exit	Nozzle Exit
	M_0 = 4.0, Q_0 = 47.9 kPa (21.7 km)				
P_s (kPa)	4.23	59.8	204.9	124.8	4.23
P_T (kPa)	676	650	433	270	251
T_s (K)	218	474	718	1691	675
T_T (K)	891	883	860	1949	1926
M	4.00	2.18	1.02	1.12	3.74
V (m/s)	1189	944	531	845	1867
	M_0 = 6.5, Q_0 = 47.9 kPa (28.1 km)				
P_s (kPa)	1.59	65.9	59.3	105.0	1.59
P_T (kPa)	5386	2366	2044	588	446
T_s (K)	225	781	779	1902	717
T_T (K)	1902	1747	1709	2521	2402
M	6.50	2.86	2.81	1.68	4.12
V (m/s)	1959	1549	1516	1341	2156

FIGURE 3.6 Schematic illustration of a hypersonic flight vehicle showing the cross section of the scramjet and temperatures of various points on the vehicle. SOURCE: Reprinted with permission from T.A. Jackson, D.R. Eklund, and A.J. Fink. 2004. "High Speed Propulsion: Performance Advantage of Advanced Materials," *Journal of Materials Science* 39(19):5905-5913.

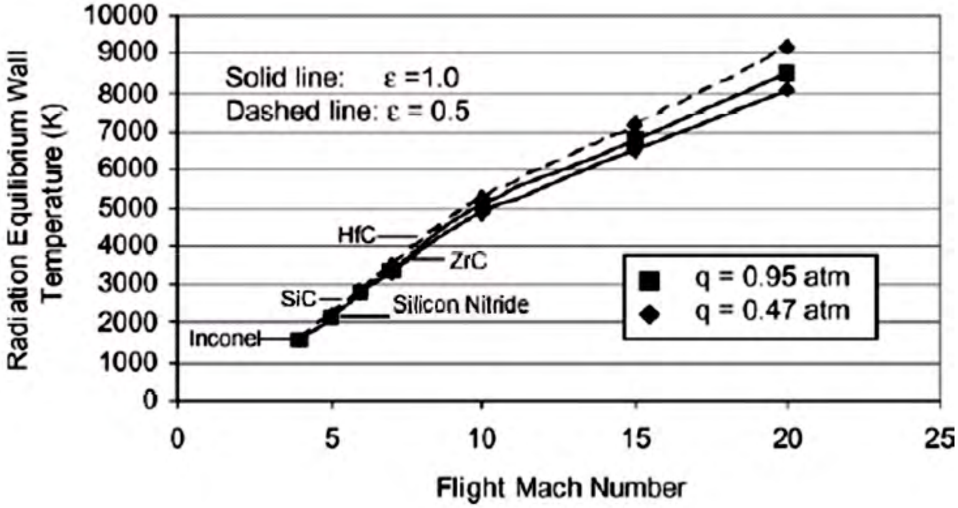


FIGURE 3.7 Predicted temperatures at the stagnation point of the leading edge of an engine cowl with a radius of one inch. SOURCE: Reprinted with permission from T.A. Jackson, D.R. Eklund, and A.J. Fink. 2004. "High Speed Propulsion: Performance Advantage of Advanced Materials," *Journal of Materials Science* 39(19):5905-5913.

explored to accommodate the extreme temperatures and heat loads include actively cooled refractory metals and passive ultrahigh-temperature ceramics.[33] Actively cooled metal designs are used in the first demonstration engines because known refractory metal alloys are available and can be machined to shape. However, later generations of engines will likely incorporate advanced ceramic components, as these offer the promise of decreased design complexity due to the elimination of cooling channels, reduced weight due to lower bulk densities, and improved environmental stability. Hybrid designs that incorporate ceramic coatings into metallic systems have also been proposed as a method to take advantage of the manufacturability of metallic components and the superior thermal stability of ceramics.[34]

To date, scramjet development has largely been limited to computer-generated design and ground-based demonstrators. Two significant programs warrant discussion here to highlight the current status of hypersonic propulsion. First, the X-43 demonstrator was flight-tested in March 2004. Images of the X-43 are shown in Figure 3.8. The X-43 was flown to 40,000 feet by a B-52, dropped, and accelerated by a solid rocket booster.[35] After reaching approximately Mach 10, a hydrogen-fueled scramjet was ignited for approximately 10 seconds to demonstrate engine operating principles. At the time of this writing, a consortium that includes the Boeing Company and Pratt and Whitney Rocketdyne is developing the X-51a Waverider concept as part of an effort funded by the Defense Advanced Research Projects Agency (DARPA) and managed by the Propulsion and Power Directorate of the AFRL.[36] In flight tests scheduled for the spring of 2010, the vehicle was to be accelerated from Mach 4.5 to Mach 6 by a hydrocarbon-fueled scramjet. Three additional tests were then scheduled at 4- to 6-week intervals following the initial test. Although these short-duration tests can use expendable materials for engine components, further development and longer-duration flights will require the use of more robust designs and materials in future vehicles. Fundamental research is needed to identify new candidate materials, and concurrent materials development is needed to transition new or existing materials into these demanding applications.

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[33] S.R. Levine, E.J. Opila, M.C. Halbig, J.D. Kiser, M. Singh, and J.A. Salem. 2002. "Evaluation of Ultra-High Temperature Ceramics for Aeropropulsion Use," *Journal of the European Ceramic Society* 22:2757-2767.

[34] C.A. Steeves, M.Y. He, and A.G. Evans. 2009. "The Influence of Coatings on the Performance of Structural Heat Pipes for Hypersonic Leading Edges," *Journal of the American Ceramic Society* 92(9):553-555.

[35] See http://www.aerospace-technology.com/projects/x43/. Accessed June 2009.

[36] See http://www.boeing.com/defense-space/military/waverider/index.html. Accessed June 2009.

FIGURE 3.8 (Left) Artist's rendering of the X-43 hypersonic flight demonstrator and (right) image of an actual vehicle during assembly. SOURCE: Images downloaded from the NASA Image Exchange Server, http://nix.nasa.gov/.

3.4.3 Rocket Propulsion

As with turbine engines and scramjets, rocket engine performance is driven by the materials used in the construction of the engine. Also as with turbines, designs that use cooling mechanisms are critical to engine performance.

Even though the specifics of operation are different, both solid rocket motors (SRMs) and liquid rocket engines (LREs) have many components in common. Both have propellant cases/tanks, combustion chambers, throats, and nozzles. One major difference is that liquid rockets require pumps to inject the fuel ingredients into the combustion chamber. These pumps represent one of the most demanding materials applications.

Solid Rocket Motor Materials

In a solid rocket engine, a solid fuel-oxidizer mixture (such as ammonium perchlorate and aluminum) is stored in a case, with the combustion taking place inside the case. The reaction of the mixture produces high-temperature gases that pass from the case through a throat and into a nozzle where they expand, producing thrust.

Case Materials

SRM cases have been fabricated from both metallic and composite materials. In the case of metallic materials, steel, titanium, and aluminum alloys have been used. Steel alloys offer excellent mechanical properties, processability, and affordability. Aluminum and titanium alloys offer high specific mechanical properties, which result in weight savings, which in turn translate into increased vehicle payloads or increased range. However, titanium is a relatively high cost material. Composite materials offer even greater weight savings compared to the metals because of their very high specific properties. Composite systems such as glass and carbon fibers have been used as candidate systems to reduce weight and increase performance.

Solid Rocket Motor Nozzle Materials

The materials used to manufacture SRM nozzles generally fall into the following groups: structural materials; housing and nonstructural materials, such as adhesives; sealants and greases; thermal insulating materials; and ablative materials. The lower-temperature housing or case materials are discussed above. The nonstructural materials are subjected to high temperatures.

Up to 200°C to 260°C, materials such as aluminum alloys and fiberglass-resin composites can be used. These materials systems have high strength-to-weight ratios, excellent corrosion resistance, and cost-effective manufacturing methods. High-strength steels may be used for thin skin sections operating at higher temperatures.

From 200°C to about 1100°C, higher-temperature iron-based, iron-nickel-based, nickel-based, cobalt-based, and iron-nickel-cobalt chromium-based superalloys may be used.

Above 1100°C, high-temperature refractory alloys such as molybdenum, columbium, tantalum, and tungsten provide property retention up to 2200°C. Above 2200°C, graphite and pyrolytic graphite may be used.[37]

Liquid Rocket Engine Materials

In a liquid rocket engine, a fuel (such as hydrogen or kerosene) and an oxidizer (such as liquid oxygen) are stored in tanks or "bottles" and, on demand, are pumped into a combustion chamber where they mix and react. The reaction produces high-temperature gases, which pass through a throat and into a nozzle where they expand, producing thrust. Gas temperatures in the chamber may exceed 3300°C, while gas temperatures in the nozzle may range from 1600°C to 2800°C. A combination of high-performance materials and cooling schemes is required for engine performance. These temperatures are too extreme for conventional aerospace materials; therefore engines must employ some type of active cooling scheme.

[37] See, for example, http://www.fas.org/man/dod-101/sys/missile/docs/RocketBasics.htm. Accessed June 2009.

To provide for coolant flow, the walls of the combustion devices are constructed of tubes or channels. During operation, coolant is pumped through the tubes or channels to keep the materials stable within their temperature limitations while this process is also serving to preheat the propellants.

Tank Materials

Common tank materials have included aluminum, stainless steels, titanium alloys, and, more recently, high-performance organic-matrix composites. In recent years the trend has been to materials that offer mass reductions, which translate into greater launch loads or increased fuel capacity. The magnitude of the mass reductions sought can only result from the use of materials with high specific properties, such as aluminum alloys and composites. In addition to light weight, aluminum offers advantages such as imperviousness to fuel leakage, corrosion resistance, and excellent fracture toughness. It is also amenable to emerging manufacturing operations such as friction stir welding. Composites offer the potential for the greatest mass reduction of all of the materials. However, in many designs, the use of an inner liner is required to prevent a loss of fuel or oxidizer and to prevent potential reactions with the propellant materials.

Combustion Chamber and Nozzle Materials

Gas turbine engine combustion processes take place at relatively lower temperatures, resulting in reduced efficiency. In addition, turbine engines use air as an oxidant. Air contains a relatively small amount of oxygen, which dilutes the reaction and lowers the combustion temperatures. Both the combustion inlet temperature and the combustion exit temperature directly affect the thermal efficiency of a gas turbine engine. The efficiency of the combustion process is nearly 100 percent in modern gas turbine engines in that the available heat release of the fuel is fully achieved. The combustor exit temperature is controlled by diluting the combustion products with air that bypasses the combustion zone. Any air used for dilution or used as a coolant either in the combustor or the turbines limits the amount of air available for combustion and represents an engine system inefficiency. The availability of higher-temperature materials would reduce the required dilution and coolant air and improve the overall turbine engine system efficiency. Since rocket engines have none of these limitations, temperatures approaching 3300°C can be achieved. Such temperatures can far exceed the melting points of the combustion chamber and nozzle materials themselves; therefore, it is critical that these materials be prevented from degrading to the point of failure. Cooling techniques, such as the propellants being passed through tubes around the combustion chamber or nozzle, are employed to give longer nozzle and chamber life. This cooling technique allows rocket engines to use more common construction materials such as aluminum, steel, nickel, or copper alloys. For example, the space shuttle's nozzle consists of 1,080 tapered stainless steel tubes that are brazed together and then brazed to an outer structural jacket made of a nickel-based superalloy. During operation, hydrogen coolant flows through the tubes to keep the nozzle materials from exceeding their melting points.

It is also possible to use uncooled nozzles that are fabricated from ablative materials. Ablative nozzles represent some of the earliest designs, in use since the 1950s. Ablative nozzles are typically constructed from composite materials of phenolic resins with various reinforcements.

The materials of choice for combustion devices in large liquid-fueled rocket engines have historically been stainless steels, nickel-based superalloys, and copper alloys. These materials are selected for their high strength and high thermal conductivity for coping with stresses and extreme thermal environments. Since these alloys also have high densities (8-9 g/cm3), their use is associated with a weight penalty.

The space shuttle main engine combustion chamber consists of an inner copper liner with 390 milled cooling channels that run axially the length of the liner. The cooling channels are closed out with a layer of electro-deposited nickel, and then an outer structural jacket made of a nickel-based superalloy is welded in place. During operation, hydrogen coolant flows through the slotted channels in the high-conductivity copper liner to keep the component cool.

3.4.4 Summary and a Look at Future Directions for Rocket Propulsion

A key future direction for rocket propulsion is to reduce the weight of the rocket engines. Lighter engines and launch vehicles would allow heavier payloads at lower costs. Innovative cooling concepts and advanced materials will help enable reductions in weight. One potential materials approach to lighter weight is the replacement of conventional high-density engine alloys with lightweight, high-specific-strength ceramic composites, such as SiC/SiC (silicon carbide fibers with silicon carbide matrices). Many materials and manufacturing issues will need to be addressed for these emerging materials to be a viable engineering approach.

The technical challenges for new materials are also accompanied by market challenges. Simply put, fewer opportunities are available for the insertion of new materials in rocket propulsion because future plans are limited by orders-of-magnitude fewer systems and fewer flights compared to those in the past. Further, as in the case of the gas turbine engines, even fewer transition opportunities are likely owing to the military sector's lack of new rocket and launch systems.

3.5 GLOBAL COMPETITIVENESS

3.5.1 The Committee's Approach to Assessment

The U.S. military and industry have been successful over the past 60 years in maintaining the military superiority and commercial competitiveness of aerospace systems, with few exceptions. Propulsion systems technologies have contributed heavily to this position, and the committee has reviewed on a comparative basis both the programmatic and investment strategies that have contributed to these advantages. Much of the past history is highly anecdotal and is subject to various interpretations; therefore the committee has made some observations based on experience, but it has relied largely on published information in making an assessment of the current and future U.S. global competitiveness.

The globalization of the propulsion industry with partnerships and international ownership of propulsion companies has to some degree blurred the definitions of the origin and application of some propulsion technologies. In addition, the devolution of the Soviet Union and the financial restructuring of much of its aerospace industry have changed the focus on its positioning of technology in the export market. In aviation, the export market technologies are present in potential threats to U.S. military forces, and in the case of space propulsion, rocket technologies and products have represented a commercial supplement to Western efforts in the area. The U.S. Air Force's Joint Strike Fighter (JSF) Program is an example of the blurring of lines of origin and application of global technologies. A foreign company, Rolls-Royce, with the purchase of Allison Engine Company, obtained a partnership position on the alternative engine for that program and a direct position on the lift fan component for the short-take-off-and-vertical-landing (STOVL) version of the aircraft. These positions brought Rolls technologies to the program, with examples being superplastically formed diffusion-bonded hollow fan blades and linear friction welding of rotating components and thrust vectoring component technologies used directly in the lift fan and nozzle systems on the JSF STOVL version of the aircraft and incorporated into the joint-venture-proposed alternate engine. The inference drawn from this experience is that there are significant materials and process technologies in other countries that rival or exceed those currently available in the United States. In this case they were complementary to the other available U.S. technology for the JSF Program and provided an attractive alternative to the U.S. technologies.

The committee has taken two approaches to assessing the issue of global competitiveness: the first is a direct review of the published activities under the European Union (EU) initiative—an example being EU status reports on European Technology Platforms[38]—and the second being a review of published papers relevant to the subject of propulsion materials technology. The first of these approaches, both of which are presented in Section 3.5.2 as international development activities, provides an indication of the focused investments that are being made to raise the competitiveness of the global industry. The second approach is an indication of the intellectual capital that is being focused on the subject to provide a longer-term return in what may be interpreted to be a focus area for future economic growth or military advantage.

3.5.2 International Development Activities

The statement of task for the present study asked whether U.S. R&D efforts would "keep the U.S. on the leading edge of propulsion technology" (Appendix A). To address this task, the committee received input data from the National Air and Space Intelligence Center (NASIC) and surveyed published open-source activities in propulsion and materials development for the following international research communities:

- European Union (European Technology Platform on Advanced Engineering Materials and Technologies [EuMaT]—responsible for European Union R&D activities in the area of advanced material and technologies)
- United Kingdom
- China
- Japan
- Russia
- Ukraine

European Union

EuMaT is the organization within the European Union that facilitates advanced research in the development and application of advanced engineering materials and related manufacturing processes.[39] EuMaT works closely with the European Materials Forum and the European Materials Research Society. EuMaT provides a technology platform to bring together government, industry, and academia to establish R&D priorities and to oversee the dispersal of funds within the European Union Research Framework Program.

[38] European Commission. 2007. "Third Status Report on European Technology Platforms at the Launch of FP7," report compiled by Commission Inter-Service Group on European Technology Platforms, Directorate-General for Research, EUR 22706 EN, March.

[39] See http://www.eumat.org/. Accessed June 2009.

EuMaT is designed to focus on all aspects of materials development and application, including the following:

- Design, development, and qualification of advanced materials (multifunctional materials, materials for extreme conditions, hybrid and multimaterials);
- Advanced production, processing, and manufacturing;
- Materials and component testing;
- Materials selection and optimization;
- Advanced modeling on all scales;
- Databases and supporting analytical tools; and
- Life-cycle considerations, including impacts, decommissioning, reliability, hazards, risks, and recyclability.

Within the EuMaT structure are individual task groups that address these aspects of materials development and application:

- Nanostructured materials (nanopowders): ceramic materials and intermetallic alloys;
- Fiber-based composites; SiC-based materials;
- Multimaterial (hybrid) systems: metals-plastic, ceramic-metals, compounds, and others;
- Materials with functionally gradient composition or structure;
- Thin or thick films and coatings: magnetic films, thermal barrier coatings, corrosion protection, and others;
- High-temperature materials: heat-sink materials, creep-resistant materials (structural materials for long-term application including lightweight aspects and oxidation resistance); in particular, metals, composites, and coating systems;
- High-strength and corrosion-resistant materials (ultra-steels, materials for bridges, marine environment, pressure equipment, and so on);
- Self-passivating materials;
- Radiation-resistant materials;
- Biomaterials (implants, ceramic artificial joints, functional materials for enhanced human well-being—e.g., antibacterial materials, isothermal materials, and so on), engineering polymers, soft materials, and others;
- Materials for microdevices; magnetic thin films, sensors, materials for memory storage, magnetic thin films, GaN, GaAlN;
- Cryogenic, hydrogen storage materials: (CeLa)–(NiCoCuFe), quasi-crystals (Ti–V–Zr–Ni), and others;
- Catalytic materials for new combustion systems (e.g., alternative fuels, microcombustors, and so on);

- Modeling of advanced materials: properties, functional behavior, simulation, predicted materials lifetime, and impacts on all scales;
- Materials production technologies for advanced materials with optimized microstructure and heat treatment and manufacturing technologies, also to include forming, shaping, welding, brazing, bonding, and similar techniques;
- Advanced materials testing, characterization, and qualification;
- Development of data systems (e.g., for material selection, material databases, simulation systems, and so on);
- Pre-normative work and standardization; and
- Dissemination: publications, conferences, Web efforts, coordination of exploitation issues.

Funding within European Framework No. 7 is estimated to exceed 4 billion euros for advanced materials development. Yearly allocations range from 500 million euros to 2.5 billion euros. This budget will be obtained through the contribution of industry (target: 35 percent), national governments (target: 35 percent), and the European Commission (target: 30 percent). EuMaT's strategic plan indicates funding of 450 million euros on intermetallics and metal-ceramic composites.

Specific projects identified by EuMaT for funding priority include the following:

- *High-temperature coating systems.* Developing and modeling of improved thermal insulation and protection systems against oxidation and corrosion. Improvement of lifetime at temperatures greater than 1200°C up to more than 25,000 hours. Increase of cyclic endurance. Self-healing coating systems.
- *Assembled blades in association with optimized materials.* Manufacturing technologies, properties of the joints also in association with coating. Development of rapid tooling and rapid manufacturing technologies. Improvement of materials: increase of creep strength (service temperature) and corrosion resistance. New types of materials (ceramic composites).
- *Improvement of rubbing and sealing systems.* For example, in the gap between blade and casing: simulation of the tip rubbing process and influences on vibration and damping, procurement of characteristic data, modeling. New deposit material in the rubbing area (avoiding damage of blade tip, high wear and oxidation resistance to keep the gap tight).
- *Ultrahigh-strength materials for rotors.* Production technology for large components, determining material properties of available materials. New materials for blades of low density and their manufacturing technique. Determination of design limits.
- *Refurbishing methods.* Process development for straight solidified, and single-crystalline materials, improved testing methods to define the degree

of damage. Repair of coatings. New joining techniques for thin walled blades. Inspection and testing after repair.

- *Lifetime modeling.* Consideration of combined loads, influence of defects if new materials will be used. Multiscale modeling of deformation and damage development. Evaluation of safety margins in order to make full use of material capacity.
- *Economic standard structural materials.* Increased thermal flexibility and extended lifetime at high temperatures requiring improvement of already-existing standard materials (e.g., casing: nodular cast iron), application at higher temperatures, improved resistance against LCF loading, new concepts to evaluate component integrity on the basis of critical flaw sizes.
- *New types of structural materials.* For example, ceramics, ceramic composites, reinforced Ni-aluminides.

Literature and patent searches indicate significant research activity in improved efficiency of turbojet/turbofan engines, ramjet and scramjets for hypersonic flight, and increased-performance liquid-fueled and solid rocket motors. An example is the work in France and Germany to develop a composite structure (C/SiC) to operate at temperatures above 1800 K in an oxidizing environment as a fuel-cooled structure for ramjets and liquid rocket motors. This work is a cooperative effort by the company MBDA France (located in Le Plessis-Robinson and Bourges); EADS Astrium Space Transportation in Ottobrunn, Germany, and Bordeaux, France; and EADS Innovative Works (formerly CRC) in Ottobrunn, Germany, and Toulouse and Suresnes, France, with some laboratories and subcontractors.[40] As noted above, this type of work is generally completed by a consortium of industry, government, and university entities with funding support from the European Union.

United Kingdom

In addition to participation in the EU Framework Program activities, Rolls-Royce and Qinetiq Plc are collaborating on the Advanced Aero-engine Materials (ADAM) project. This project will focus on high-temperature turbine materials and is funded at 4.7 million pounds (approximately $7.5 million at a 2009 exchange rate) by the Defense and Research Partnership. Specific areas of focus include metals and ceramics for high-temperature applications, and nanostructured materials and coatings for thermal and erosion protection.

[40] M. Bouchez and S. Beyer, "Ptah-Socar Fuel-Cooled Composite Materials Structure: 2009 Status," paper presented at 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference, October 21, 2009.

China

Within China, the largest research institute for aeronautical materials, thermal processing, and materials testing is the Beijing Institute of Aeronautical Materials (BIAM). BIAM's role is to provide the basic research for high-performance materials and then to provide industry with the expertise to transition this research. Advanced materials have been identified as key fields in China's national R&D system (National High Technology Research and Development Program—863 Program, and National Basic Research Program—973 Program). Domestic leaders within China include Sinoma Advanced Materials Co., Ltd., and Shenyang Starlight Advanced Ceramics Co., Ltd.

Published abstracts and paper submissions to the American Institute of Aeronautics and Astronautics (AIAA) and patent submissions indicate considerable research activity in the application of ramjet, scramjet, and combined-cycle propulsion concepts for hypersonic flight (Mach 3 to Mach 6.0).

Japan

Battelle-Japan consists of a team of materials scientists focused on the development and life-cycle analysis of advanced ceramics, coatings, nanomaterials, and thin film deposition. Industry surveys indicate a strong position in the research and application of ceramics and ceramic-matrix composites. A survey in 1991 cited on the GlobalSecurity.org website stated: "Japan may be the world leader in advanced ceramic research and development."[41]

The Japan Aerospace Exploration Agency has established the Japan Ultra-High Temperature Materials Research Center to advance the research and development of ultrahigh-temperature materials. This research center comprises two facilities necessary for handling ultrahigh-temperature materials of over 2000°C, creating new materials (ultrahigh-temperature dissolution, ultrahigh-temperature and -pressure sintering), and performing analysis and evaluation. These facilities were established under the basic research improvement plan of the Energy and Industrial Technology Development Organization.

Published papers indicate significant research into scramjets, combined-cycle, turbojet, and turbo-ramjet engines for hypersonic flight. Patent applications by the Japanese National Aerospace Laboratory focus on hypersonic research.

[41] General Accounting Office, National Security and International Affairs Division. 1991. *Aerospace Plane Technology: Research and Development Efforts in Japan and Australia* (GAO/NSIAD-92-5). Washington, D.C.: Government Printing Office, p. 113.

Russia

The All-Russian Scientific Research Institute of Aviation Materials (VIAM) conducts the majority of aeronautical materials research in Russia. Its research includes casting superalloys for turbine blades. VIAM claims significant benefits of its intermetallic alloys over Ni-based alloys in service life and cost. It also has applications related to cobalt aluminate surface treatments to improve blade performance and durability. VIAM also developed a vacuum plasma high energy technology method for coating and providing surface treatment of ME-Cr-Al-Y alloys.

AIAA-published papers address ramjet and scramjet research for hypersonic (Mach 6 range) applications and general research on pulse-detonation propulsion concepts by the Russian Academy of Sciences and the Central Institute of Aviation.

Within the Russian Federation, NPO Energomash has a long history of success in designing and manufacturing liquid-fuel rocket engines. These engines are used in other international launch vehicles such as the United Launch Alliance (U.S.) Atlas V, the SeaLaunch (U.S.-led joint venture) Zenit, and the South Korean Naro-1.

Ukraine

Pratt and Whitney Division of United Technologies Corporation has established a collaborative research venture with the Paton Research Institute in Kiev. The research is focused on developing new materials using electron-beam deposition processing.

Conclusion

Although the results of the literature and patent searches referred to at the beginning of Section 3.5.2 do not allow a complete assessment of the state of the art of international propulsion and materials development, they do indicate significant activity and investment. In particular, the focus on advanced ceramics in Japan and the focus on intermetallics and metal-ceramic composites by the European Union will certainly create centers of excellence with the capability to rival or exceed U.S. capability. The EU approach of requiring a consortia of government, industry, and academia to pursue EU funding brings together the best talent and resources, and it may be an operating model for consideration for some areas of future U.S. materials development.

The EuMaT vision is to establish the leading global position in materials technology and to have Europe emerge by 2020 as a leader in the development and utilization of advanced material solutions and manufacturing processes.

3.6 THE PLAN

Discussions with personnel in the Materials and Manufacturing and the Propulsion and Power Directorates of the AFRL indicate that the directorates address three broad categories of military needs in the area of materials research: (1) near-term needs: rapidly deliver technical innovation, driven by warfighter emergencies; (2) intermediate-term needs: develop technology options that meet the needs of capability developers; and (3) far-term needs: conduct long-term research, driven by a bold technology goal. These categories align with the Focused Long Term Challenges approach to capability planning currently employed by the USAF.

It was reported that 80 percent of the Materials and Manufacturing Directorate's funding is directed toward the long term. The immediate needs of the warfighter are addressed by committing staff as needed to solve short-term issues.

As materials in propulsion systems become more mature and reach high TRLs or MRLs (moving from 6.2 programs to 6.3 or 6.4 activities), the requirements are driven by the Propulsion and Power Directorate or specific program offices. Directorate funds for the nearest-term requirements were estimated to be approximately 3 percent of the materials R&D budget,[42] since the majority of these costs are in the fielded-systems operational budgets. In addition, there is a special Laboratory Director's fund of approximately $1 million per year, as noted in Section 3.2.1, to support new material systems or new processes. A portion of the directorate's budget is used to address fielded-system support issues; however, the majority of this type of directorate work that addresses problems arising in fielded propulsion systems is funded by the specific program offices or other organizations.

3.6.1 Review of Relevant Focused Long Term Challenges and Roadmaps

In assessing propulsion material technology needs, the committee reviewed a wide range of Air Force requirements and planning and implementation activity. One of the difficulties in assessing the relative adequacy of the propulsion materials program(s) in comparison to the successes and failures of the past results from the changing mission requirements and evolving technologies in the area. This complexity is well stated in a report summarizing a group of materials and propulsion technology workshops held at Wright-Patterson AFB in 2008.[43]

> The USAF is entering a period of rapidly evolving new technologies. In propulsion, the new programs in air and space propulsion and power are producing war-winning concepts,

[42] J. Arnold, K. Stevens, Col. W. Hack, C. Stevens, and C. Ward, presentations to the committee, Wright-Patterson AFB, Ohio, May 27, 2009.

[43] AFRL, *Materials for Advanced Aerospace Propulsion and Power Systems,* AFRL/RZ and AFRL/RX Workshop, AFRL-RZ-WP-TM-2008-2127, 2008.

> which will enable enhanced vehicle payload, range, and loiter capability. There are also emerging totally new weapon classes, such as hypersonic vehicles with very high heat loads, and directed energy weapons with escalating demands for very high power, each requiring advanced components and a closely integrated thermal management system strategy. In addition, both legacy and pipeline systems must be sustained and retrofitted with improved capability and robustness.

The degree of complexity of evolving requirements and technologies is further reinforced when one reviews the Focused Long Term Challenges (FLTCs) approach[44] to defining capabilities needed to address the Air Force current and future missions that include strategic needs for the following:

- Global strike;
- Homeland security;
- Global mobility;
- Space and command, control, communications, computers, intelligence, surveillance, and reconnaissance;
- Nuclear response; and
- Global persistent attack.

Meeting these needs is further complicated when the integration challenges are associated with addressing and implementing solutions in the following areas:

- Air vehicles,
- Sensors,
- Information acquisition and management,
- Directed energy,
- Human effectiveness,
- Space vehicles,
- Materials and manufacturing,
- Munitions, and
- Propulsion.

The Air Force has segmented these needs by time periods that impose the added requirements of operating with a high degree of both urgency and vision. The segments are defined in terms of the following:

- *The near term.* Rapidly deliver technical innovation, driven by warfighter emergencies—reshape today's battles (Today).

[44] Leo Rose, AFRL, "Focused Long Term Challenges (FLTC)," presentation, March 18, 2008.

- *The intermediate term.* Develop technology options that meet the needs of capability developers—shape today's Air Force (4 years plus).
- *The far term.* Conduct long-term research, driven by a bold technology goal—shape the future Air Force (12 years plus).

Eight Focused Long Term Challenges are represented in the Air Force plans:

1. Anticipatory Command, Control, and Intelligence (C2I);
2. Unprecedented Proactive Intelligence, Surveillance, and Reconnaissance;
3. Dominant Difficult Surface Target Engagement/Defeat;
4. Persistent and Responsive Precision Engagement;
5. Assured Operations in High Threat Environment;
6. Dominant Offensive Cyber Engagement;
7. On-Demand Force Projection, Anywhere; and
8. Affordable Mission Generation and Sustainment.

Examining the FLTC document[45] provides insight into the weapons system requirements and in turn the propulsion system figures of merit and the resulting leverage that propulsion materials technology will have on a mission.

FLTC 1 (Anticipatory Command, Control, and Intelligence) requires battlespace awareness and the synchronized management of battlespace effects that require the discovery of threatening systems and objects and fully effective C2I operations. This implies a range of surveillance aircraft from small to large high-altitude unmanned aerial vehicles (UAVs) and manned subsonic platforms in addition to satellite assets.

FLTC 2 (Unprecedented Proactive Intelligence, Surveillance, and Reconnaissance) dictates effective surveillance capability with real-time high-performance networking with persistence. The weapons systems to meet a portion of this challenge are the same as those of FLTC 1; however, in addition, a requirement for large manned aircraft with persistence and large electrical power requirements is defined.

FLTC 3 (Dominant Difficult Surface Target Engagement/Defeat) introduces the emergence of the requirement for the micro-UAV that can enter complex urban environments and help direct scalable kinetic and nonkinetic effect to difficult targets, including chemical, biological, radiological, nuclear, and explosives (CBRNE) threats.

FLTC 4 (Persistent and Responsive Precision Engagement) addresses the more traditional Air Force role of responsive precision engagement with the requirement for global delivery of the full spectrum of nonkinetic and kinetic effects.

[45] AFRL, *Materials for Advanced Aerospace Propulsion and Power Systems*, AFRL/RZ and AFRL/RX Workshop, AFRL-RZ-WP-TM-2008-2127, 2008.

The resulting systems include both stealthy and high-Mach-number manned or unmanned vehicles.

FLTC 5 (Assured Operations in High Threat Environment) puts further emphasis on stealth and information gathering and management. In addition, it introduces the possible use of unmanned combat air vehicles (UCAVs) in both traditional battlespaces and urban environments.

FLTC 6 (Dominant Offensive Cyber Engagement) puts emphasis on electronic systems, and it also defines requirements for a variety of both large and small surveillance platforms and the early warning aircraft of the future.

FLTC 7 (On-Demand Force Projection, Anywhere) identifies weapons systems at two ends of the flight spectrum. The more traditional role of global projection of ground forces and materiel anywhere in the world in any weather falls to the large air transport vehicles, while the requirement for rapid response and access to space defines a need for very-high-Mach-number or hypersonic systems.

FLTC 8 (Affordable Mission Generation and Sustainment) addresses affordability and sustainment of all missions and addresses an area that for propulsion materials and operating systems is considered a key element for successful implementation of materials systems and robustness of the final product. The related qualification and support systems for propulsion are necessitated by this requirement, with the challenge being quantification.

The committee's review of the generation of specific propulsion-materials-related requirements included briefings by personnel from both the Materials Lab and the Propulsion and Power Lab, briefings by the three U.S. engine manufacturers, a briefing on ONR activities in the area, a visit by a committee subgroup to the Materials and Manufacturing Directorate at Wright-Patterson Air Force Base, a series of USAF reports on the subject dating back to 2002, and historic data dating back to the early 1990s.

Product taxonomy has been used to reduce the capabilities defined in the FLTCs to attributes and to propulsion "products" that in turn define materials requirements for significant advances in capabilities. These products are identified as turbine engines, both liquid-fueled rocket engines and solid rocket motors, and scramjets.

For each of these product areas, requirements have been identified for the focus of materials research and development. In the case of turbine engines, these include hybrid disk systems, SiC/SiC CMCs, fluids and lubricants, and preventive maintenance checks and services. The materials requirements for liquid-fueled rocket engines include high-pressure oxygen-compatible Ni-based superalloys, high-stiffness Al alloys, and SiC/SiC CMCs. The solid rocket motor material requirements defined by this process include advanced cyanate ester composites, advanced refractory carbides, and carbon-carbon composites. The scramjet analysis yielded material requirements in the areas of advanced thin-gauge metals, SiC/SiC and C-SiC CMCs, and carbon-carbon composites.

The turbine engine material requirements have been clearly articulated through the VAATE Program, which builds on the institutionalized process developed under the past IHPTET Program that was led by the DOD Office of DDR&E and featured the Air Force as the major participant.[46] This program addressed large turbine engines and identified the requirements for increased capabilities as follows:

- The main barriers to increased performance:
  — Compressor pressure ratio (Compressor exit temperature)
  — turbine temperature
  — component efficiencies and
  — cooling flow

These are in turn stated in terms of materials:

- Material limitations
- constrain pressure ratio and
- turbine temperature

This program provides a direct linkage between the capabilities, the propulsion requirements, and the materials development activities within the Air Force and the manufacturing community.

In the case of the liquid-fueled rocket engines, the materials programs recognized a series of materials advances as noted above; however, the linkage to new systems' requirements[47] was not as clear as that noted in the turbine engine work. One requirement noted in the liquid rocket engine review was that there be a continental United States (CONUS) source for high-temperature composites, since the primary source for these materials is currently Japan, and the government of Japan places export restrictions on the use of these materials for certain weapons systems.

The committee could not find propulsion requirements for the small or micro-UAV that address the capabilities of FLTC 2 in the area of effective surveillance capability with real-time high-performance networking in the urban battlespace.

3.6.2 Overview of the Plan

The Materials and Manufacturing Directorate and the Propulsion and Power Directorate of the Air Force Research Laboratory have a history of working together to formulate coordinated materials development and applications planning. The current effort in this area was brought into focus through a series of workshops

[46] Charles W. Stevens, Chief, Turbine Branch, AFRL/RZTT, "Versatile Affordable Advanced Engine Program (VAATE)," briefing to the committee, July 20, 2008.

[47] Drew DeGeorge, Edwards AFB, "Rockets," briefing to the committee, July 22, 2008.

that incorporated the Air Force Future Long Term Challenges into this planning and generated a set of agreed-on responses for the two directorates addressing a range of notional future platforms.

The approach is an interactive examination of capabilities, concepts, advanced propulsion and power (options), and materials. The interactive nature of the process entails iterations between each of these elements of the AFRL directorates' capabilities and their charters within the 6.1, 6.2, and 6.3 funding categories.

The planning process recognizes that USAF is entering a period of rapidly evolving new technologies and that there are also emerging totally new weapons classes, such as hypersonic vehicles with very high heat loads, and directed-energy weapons with escalating demands for very high power. The planning also recognizes that the product of the planning would have to fit within constrained budgets dictated by the current R&D funding environment. In this context the group authoring the plan identified 18 key technology areas extending across the spectrum of air-breathing propulsion. Materials research and development investments needed for USAF to maintain leadership in propulsion and power were identified; these investments would advance the state of the art in the 18 key areas to readiness levels needed for component development. Specific funding recommendations to address the critical materials limitations were made, and the allocation to each of the 18 areas was recommended, as was timing of the funding.

The planning also recognized several issues concerning U.S. military access to critical technologies in the global marketplace: for example, battery materials, magnetic materials, energetic materials, high-strength fibers, and refractory alloys. It was noted by the committee that the AFOSR could play a significant role in bringing these technologies to a higher level of readiness through further joint activities; however, it was noted that the workshops did not include representatives from the warfighter, the system program office organization, or the AFOSR. The committee thinks that the inclusion of these groups is essential to formulating a successful materials strategic plan. The plan does not address alternative techniques for coping with the realities of current and future budget pressures on materials development funding—techniques such as encouraging collaboration among domestic competitors, among competitors and suppliers, among universities, among universities and companies, and among international entities.

The committee's assessment of this planning was based on the Air Force document *Materials for Advanced Aerospace Propulsion and Power Systems*[48] and was conducted as a review and evaluation of the USAF strategic plan for materials research and development to support future propulsion and power needs of the USAF. No other sources were consulted. Some of the material in the plan reviewed

[48] AFRL, *Materials for Advanced Aerospace Propulsion and Power Systems*, AFRL/RZ and AFRL/RX Workshop, AFRL-RZ-WP-TM-2008-2127, 2008.

by the committee is ITAR-controlled, and the details of the committee's assessment are provided in the ITAR-restricted text of Appendix D. Only a brief, unrestricted summary of the assessment process is included here.

3.6.3 Assessment of the Plan

The committee's assessment used seven questions employed in evaluations of strategic plans. Following is a brief (unrestricted) summary of the committee's evaluation of the plan with respect to each of the seven questions:

1. *Is there a logical process that defines the development of the strategic plan?* The approach used in the workshops followed a well-developed roadmapping technique that provides a logical, well-defined, iterative process that guided the development of the strategic plan. The process is wholly contained within the Materials and Manufacturing Directorate and the Propulsion and Power Directorate of the AFRL and collaboration between the two directorates, but did not include the warfighter, representatives of system program offices, or the AFOSR.
2. *Is the strategic plan based on reliable, documentable data and information?* The critical input data and information based on USAF needs have been interpreted and expressed as a set of eight FLTCs. There is no evidence that the USAF major commands have been directly consulted to determine USAF needs other than through their participation in the original definition of the FLTCs.
3. *Does the strategic plan contain realistic risk assessments?* The strategic plan lists relative assessments of payoff, technical competency, technical risk, resource risk, transition opportunity, and FLTC relevance for each of 18 development opportunities. Specificity with respect to how various risks are determined is lacking.
4. *Does the strategic plan contain milestones and resource allocations?* The strategic plan contains detailed roadmaps, goals, milestones, and associated resource needs for each of the 18 development opportunities and system payoffs that are defined. The linkage to resource (fiscal) needs is less well defined.
5. *Does the strategic plan contain an implementation component?* The strategic plan does address implementation of the plan using very high level roadmaps. A role for industry is clearly mentioned but left undefined in the strategic plan. Implementation duties and responsibilities for government and academia are not offered as should be done in a well-structured strategy.
6. *Does the strategic plan contain an assessment component?* The strategic plan does not present the formal section on assessment that is usually found in plans of this type. An oversight advisory board charged with guidance of

the initiatives recommended in the strategic plan is not discussed in the document.

7. *Will the strategic plan accomplish its goals, if properly implemented?* The detailed roadmaps do not address the complexity and interconnectedness of the development opportunities and the FLTCs. The plan lacks sufficient recognition of the inadequacy of the flow of new technologies from the AFOSR and other sources. The goals are attainable within the strategic plan as written, but there is a risk of loss of efficiency and the variability of funding and the recognition of opportunities for domestic and global collaboration.

3.6.4 Summary

The Air Force has in place a development process and organization that have been used for structural materials R&D in the past and that have produced a series of successful propulsion systems and excellent weapons platforms. Some excellent work is currently under way in both the basic and applied materials R&D areas and in planning; however, these areas address only a small part of the propulsion spectrum. The reduced national emphasis on this technology area is exemplified by a reduction in the budgets of the Materials and Manufacturing and the Propulsion and Power Directorates and by the number of competitive demonstrator engines used to transition advanced materials to new and existing systems and does not appear to be adequate to meet future Air Force needs. The deficiency in meeting the needs is compounded by this reduction in emphasis on propulsion and related materials, the increased requirements generated by the broader missions being defined by the Focused Long Term Challenges, and the growing competitive global systems capabilities resulting from other nations' focused investments in propulsion materials technology. Of specific concern are areas such as composite-fiber manufacturing in which the United States is entirely dependent on foreign sources for materials for future weapons systems.

3.7 FINDINGS

The Materials and Manufacturing Directorate and the Propulsion and Power Directorate of the Air Force Research Laboratory and the AFOSR have cooperated in the past through the institutionalized 6.1, 6.2, and 6.3 funding categories and formal programs such as the IHPTET Program to provide USAF and the U.S. industry a global competitive advantage in propulsion technology and fielded systems; however, the current VAATE Program does not have the same level of industrial competition and funded materials support as in the past, and indications are that future 6.3 demonstrator programs will see further reductions in these areas.

Finding: Current and future AFRL engine programs will have a decreased level of industrial-base cooperation and materials funding.

The transition from basic research to applied research to advanced development to manufacturing technology is not characterized by an executable process but rather is conducted on an ad hoc basis responding to "user pull" and competitive imperatives.

Finding: The Air Force has had a formal process for the transition from basic to applied research that may not be directly applicable to the current budget and broadened mission environment.

The current planning process of the AFRL Materials and Manufacturing Directorate and Propulsion and Power Directorate recognizes the need for activities in the near term, intermediate term, and far term to address the full spectrum of the Air Force mission, but the expanded scope has put significant pressure on the materials propulsion funding profile.

Finding: The current planning process of the AFRL Materials and Manufacturing Directorate and Propulsion and Power Directorate is evolving to address the FLTC approach.

The reduction in the number of technology demonstrators has significantly reduced the number of opportunities to demonstrate advanced materials and processes prior to insertion in existing and emerging propulsion systems. Although the number of new systems planned is decreasing, advanced materials are critical in improving existing and emerging propulsion systems.

Finding: Advanced materials are critical to further improving existing systems and in developing new systems. Specifically, high-temperature materials are required to increase the compressor exit and turbine inlet temperatures for improved fuel efficiency and high-Mach-number capabilities as identified in the joint planning of the Materials and Manufacturing and the Propulsion and Power Directorates.

Finding: The United States has lost its competitive advantage in the areas of attachment of compressor and fan blades using advanced welding processes, superplastically formed diffusion-bonded hollow fan blades, and some areas of ceramic-matrix composites.

3.8 RECOMMENDATIONS

Recommendation: The Air Force Research Laboratory's Materials and Manufacturing Directorate and Propulsion and Power Directorate need to develop a strategy to maintain or regain U.S. preeminence in propulsion materials. The strategy should include the regular review and updating of the directorates' propulsion materials plan, with an emphasis on the consequences of unfunded items, the changing external environment, and maintaining a balance for the near-, mid-, and far-term activities in response to the Focused Long Term Challenges and funding commitment.

Recommendation: The AFRL Materials and Manufacturing Directorate and Propulsion and Power Directorate should increase their communication and collaboration with the AFOSR, system program offices, industry, and academia relative to propulsion materials needs, advances, technology readiness, and the potential systems payoffs of technology insertion.

Recommendation: To maintain or regain the U.S. military competitive advantage in the areas of propulsion materials and to keep the United States on the leading edge of propulsion technology, there is a need for advocacy within the Office of the Secretary of Defense/Director, Defense Research and Engineering, to increase activities in new materials development and competitive 6.2 component and 6.3 demonstrator programs.

Additional detailed findings and recommendations that are related to the ITAR-controlled plan are provided in restricted Appendix D, the text of which is not releasable to the public.

4

Intellectual Property and Export Control

It is noted earlier in this report that funding for materials development for propulsion systems has been on the decline. This decline has occurred as the pace of major system development has slowed and as the cost and schedule problems on major programs have worsened. Also, in recent years greater emphasis has been placed on the development of new and exotic materials. The Materials and Manufacturing Directorate of the Air Force Research Laboratory (AFRL) has significantly redirected its emphasis and funding toward non-engine materials research and development (R&D), in areas such as electronics and nanomaterials.

It is also pointed out above that the propulsion materials cycle is considerably longer than the actual engine development cycle. As a result, decision makers are faced with a need for extraordinary patience and tenacity in resource decisions. If engine materials development is to continue, government funding organizations and corporations must be willing to bear these long-term, critical resource burdens. Materials development, by its nature, is a very expensive proposition, which companies are understandably reluctant to fund on their own. An alternative, which is increasingly attractive to engine companies, is collaborative materials development with other domestic corporations, international partners, and universities.

This chapter briefly discusses some of the issues with U.S. capabilities, difficulties with international collaboration brought on by export control regimes, and some examples and possibilities for pre-competitive collaborations in order to address one of the tasks in the committee's statement of task: "Consider mechanisms in place that retain intellectual property (IP) securely and how IP might be secured in future R&D programs" (see Appendix A for the full statement of task).

The committee did consider the commercial engine market, since it powers many military platforms.

4.1 COLLABORATIVE MATERIALS DEVELOPMENT AND INTELLECTUAL PROPERTY

As recently as the 1980s, engine rivals did not engage in collaborative materials development. Materials engineering interactions among competitors were limited largely to participation in engineering standards committees and professional society technical symposiums and committee meetings. Engine company managers, acknowledging the need and benefits, endorsed participation in such meetings, and participating materials engineers understood well the importance of not divulging competition-sensitive or proprietary information. It was a competitive era during which engine manufacturers made significant investments in advanced materials that provided real competitive advantage, and therefore they did not disseminate technical information related to their work prior to obtaining patent protection.

Additionally, aerospace corporations were, then as now, further constrained by U.S. antitrust laws. Although these laws focus principally on anticompetitive behavior such as price-fixing or cooperative marketing, more generally they pertain to any interaction among competitors deemed as anticompetitive, even those interactions involving engineers and strictly technical matters. In an effort to minimize compliance risk, corporate legal staff often monitor and regulate the contact of employees with those from rival companies. Oversight and concern are lessened when it is clear that interaction among engineers from competing companies involves pre-competitive technology, and particularly when the interaction occurs by invitation of the U.S. government.

Basic research to expand materials science knowledge, such as that typically conducted by universities, generally is understood to fall within the bounds of the pre-competitive classification. In contrast, technology and information gained through product-centric materials R&D are traditionally classified as competition-sensitive and are protected by controls on proprietary information or by legal patents. Materials and processing inventions are protected by patents, whereas materials information critical to the design of the engine product (such as company specifications, quality plans, drawing notes, design data practices, materials property minimum curves, and materials-related design practices) is protected through safeguards for proprietary information.

Toward the late 1980s and early 1990s, engine companies began to collaborate with universities, government laboratories, suppliers, and even competitors in the area of materials research and technology development. Three factors led to industrial cooperation in materials research programs. First, engine manufacturers were reluctant to accept individually the full cost of developing new materials because new materials classes, such as metal-matrix composites, were technically risky, and new aerospace alloys were expected to offer only marginal benefit.

Second, customers of the Department of Defense (DOD) and NASA also understood the high cost and risks of materials development; consequently, DOD and NASA sought to encourage industrial collaborative materials R&D and often cost sharing—thereby avoiding duplicative government materials investment while widening the benefit to multiple engine producers. For example, the Defense Advanced Research Projects Agency (DARPA) funded, among others, GE Aircraft Engines and Pratt and Whitney to conduct the High Performance Composites Cooperative Arrangement to develop basic metal-matrix and ceramic-matrix composites technology; and NASA sponsored GE Aircraft Engines and Pratt and Whitney to carry out the Enabling Propulsion Materials Program as part of the High Speed Civil Transport initiative.

Third, engine manufacturers began to understand that the competitive advantage of their engine products was only marginally influenced by materials technology. Like other industrial sectors (e.g., automotive) that use a common suite of materials, engine manufacturers emphasized competition based on engine design, performance, and price. Of course, excellence in engine design and performance does require the creative and skilled application of state-of-the-art aerospace materials.

An example of a successful industry approach to collaboration is the semiconductor industry, which was at one point in the 1980s in serious decline in the face of fierce international competition. In a research paper on the computer chip industry in general and the success of the SEMATECH consortium in particular, Carayannis and Alexander state:[1]

> The exact mechanism driving the resurgence of the U.S. semiconductor industry is too complex to ascribe to a few factors, but recent analyses have identified several trends contributing to the recovery process [including the following:]. . . .
>
> - Increased collaboration among U.S. semiconductor firms and their equipment suppliers. . . .
> - Improved cooperation, communication, and research collaboration among semiconductor firms, the Federal Government, and universities. . . .
> - U.S. semiconductor firms demonstrate an unprecedented level of horizontal and vertical cooperation with other companies including domestic and foreign competitors, suppliers, and end users. Since [the 1980s], there has been [a move] toward increasing collaboration. . . . evident in several areas:
>   — Relaxation of anti-trust laws. . . .
>   — Formation of research consortia composed of dominant firms in an industry. . . .

[1] E.G. Carayannis and J. Alexander. 2004. "Strategy, Structure, and Performance Issues of Precompetitive R&D Consortia: Insights and Lessons Learned from SEMATECH," *IEEE Transactions on Engineering Management* 51(2):226-232.

— Increase of industry-sponsored research at universities and industry-supported university research centers. . . .
— Emergence of government-university-industry strategic partnerships (GUISP) in research and development to support specific industry sectors. . . .[2]

Collaborative materials R&D was and remains a win-win proposition for U.S. government customers and cooperating engine companies. Over the past two decades, numerous such programs have significantly advanced materials technology through the development of new materials and processes, as described earlier in this report. Also, collaborative research has fostered the development of Integrated Computational Materials Engineering (ICME) technologies and their application to accelerate the insertion of materials through DARPA sponsorship.

In 2004, a panel discussion was held as part of the 10th International Symposium on Superalloys to discuss collaboration for materials development. The meeting focused on identifying the benefits of collaboration and the essential ingredients for success, including those associated with intellectual property (IP). A published summary of lessons learned included the following:[3]

- Government leadership is important in identifying the collaborative technical domain, encouraging collaboration, and helping foster cooperative, trusting relationships among team members. This governmental leadership also lessens legal concerns.
- Collaboration among competitors is most successful when each has comparable capabilities and expertise in the chosen research area. When this condition is met, collaborators view sharing ideas as a win-win opportunity.
- Collaboration can only begin after execution of a legally binding agreement on contractual terms and conditions, statement of work, and intellectual property rights. Importantly, collaborating companies must agree on how IP ownership will be determined and when intellectual property ownership will be shared.
- Researchers from competing companies must remain ever vigilant to assure that team interactions and information exchange are limited to the research topic of the collaboration agreement.

Collaboration between competing companies, focused principally on precompetitive research, has borne numerous successful developments that benefit both collaborating engine companies and, arguably, the entire materials community. It remains essential that engine producers safeguard pre-existing competition-sensitive information and intellectual property and that collaborative agreements fairly distribute or share newly developed IP and data rights.

[2] Note that the references cited in the original have been omitted from this quoted material.
[3] R. Schafrik, L. Christodoulou, and J.C. Williams. 2005. "Collaboration Is an Essential Part of Materials Development," *Journal of Metals* 57(3):14-16.

4.1.1 Finding

Finding: Aerospace materials researchers (from engine manufacturers, suppliers, academia, and government laboratories) have successfully instituted acceptable terms that provide for the disposition of and properly safeguard intellectual property and have participated in successful collaborative research programs to develop pre-competitive materials technology while reducing community-wide development risk and cost.

4.2 GLOBALIZATION

The value and need for increased collaboration are recognized in Section 4.2, but it must be further noted that the United States is no longer the leader in many areas of materials technology. As a result, this nation must consider not only the imperative of collaboration among U.S. companies but also, where appropriate, international agreements.

Presented here and in the sections that follow are assessments extracted from the 2005 National Research Council report *Globalization of Materials R&D: Time for a National Strategy* that remain timely with respect to the topics addressed in this chapter.[4]

> The United States and other leading industrial nations are experiencing the globalization of MSE [materials science and engineering] R&D. While R&D is moving offshore to support manufacturing facilities in central Europe and Asia, a much more important aspect of globalization is the massive and accelerating investments that foreign governments, most notably China and India, are making in their own R&D infrastructures. . . . This trend is occurring at a time when such investments in the United States are falling. . . . Even if the United States makes great efforts to maintain control of U.S.-generated technologies, knowledge, and capabilities, other governments' investments in their own MSE R&D will challenge the ability of the United States to lead technologically. It is, therefore, in the long-term interest of the United States to participate in international partnerships in MSE R&D and thereby ensure U.S. access to cutting-edge knowledge and technology.

4.3 CRITICAL ENGINE MATERIALS

The United States has been at or near the forefront of the research and development of advanced electronic materials and nanotechnologies and biomaterials, but it has lost or is losing technical capabilities in those areas most critical to advanced propulsion system design and development.

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[4] National Research Council. 2005. *Globalization of Materials R&D: Time for a National Strategy.* Washington, D.C.: The National Academies Press, p. vii.

4.3.1 Alloys

As pointed out in *Globalization of Materials R&D*:[5]

> Patent applications in the alloys subfield are dominated by inventors in the United States, Japan, and Western Europe. U.S. activity remained fairly steady from 1979 to 2004, at around 550 patents a year. Japan significantly increased its absolute number of patents (from 251 to 653 in the period reported), and its share (relative to that of the United States) surged, surpassing the U.S. share in the mid-1990s. Western Europe has had a steady increase in activity, with its share relative to the U.S. share increasing by 50 percent over the last 25 years.

A 2000 benchmarking report concluded that "in all probability, the U.S. lead will remain, but that is not a certainty."[6] "Research into the production, processing, and development of metallic materials in the United States has continued to decline since 1998. Very little alloy development is being done by metal producers, which formerly did most of this work, and companies in the metal-consuming industries have also decreased their efforts."[7]

4.3.2 Ceramics

According to *Globalization of Materials R&D,* "Patents in ceramics are dominated by the United States and Japan. The number of patents with inventors in Japan jumped significantly at the beginning of the 1980s, and activity there recently appeared to be on a par with the United States. . . . Japan may have equaled or even surpassed the United States in the last decade."[8] Additionally, France has a significant effort in the area of ceramics for high-temperature propulsion needs.

4.3.3 Composite Materials

Globalization of Materials R&D states:[9]

> In the field of composite materials there has been a noticeable increase in global research, with patent output from the United States, Asia, and Europe about equal. Activity in Europe is dominated by Germany and France. Patent output by inventors in Italy shows a significant upward trend, while activity in the United Kingdom and Switzerland remains

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[5] Ibid., p. 36.

[6] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. 2000. *Experiments in International Benchmarking of U.S. Research Fields*. Washington, D.C.: National Academy Press. Referred to hereinafter as the "2000 benchmarking report."

[7] National Research Council. 2005. *Globalization of Materials R&D: Time for a National Strategy.* Washington, D.C.: The National Academies Press, p. 75.

[8] Ibid., p. 37.

[9] Ibid., pp. 37-38.

static. The United States appears to have lagged behind Japan in the mid-1980s but has caught up since. Taiwan and Korea have been active, but overall numbers remain low. . . .

4.3.4 Modeling and Simulation

As pointed out in *Globalization of Materials R&D:*[10]

> The 2000 benchmarking report stated that computer modeling of material processing was the strength of the U.S. industry. Indeed, some industries today are utilizing computer-based models of solidification and mechanical working, but it is not true that the United States is ahead of the rest of the world in this area. Developers and researchers in Japan and Europe have provided many of the models used in the metals industry for process modeling and control.

These extracted assessments suggest that the United States appears to be losing its leadership, and there are no indications that this trend is going to be reversed any time soon.

4.4 COLLABORATION AND INTELLECTUAL PROPERTY

Collaboration with foreign entities, which may become increasingly important if the United States is to retain access to advanced engine materials and technologies, appears to be very limited. In addition, concerns over the handling and protection of intellectual property dominate the thinking of U.S. firms. Again, as noted in *Globalization of Materials R&D:*[11]

> Respondents who reported some international element to their research activities were asked to clarify the international nature of their work (Table 2.1).

TABLE 2.1 Nature of International Collaboration

Type of Collaboration	Share of All Collaborations (%)
U.S. academic-foreign academic research	54.5
U.S. corporate-foreign corporate research	14.1
U.S. academic-foreign corporate research	6.5
U.S. corporate research carried out by foreign affiliates of the U.S. corporation	12.3
U.S. corporate research carried out with joint ventures and/or by contract with foreign corporation(s)	12.6

NOTE: Results of questionnaire sent to MSE researchers who self-identify as being in the United States and carrying out research with an international aspect. (These data are indicative only and not based on a statistically relevant sampling.)

[10] Ibid., p. 75.
[11] Ibid., p. 42.

Globalization of Materials R&D also states:[12]

> Thirty-eight percent of the respondents said that robust protection for IP was critical and entered into their decision on where to base R&D more than any other business factor. Another 46 percent of respondents ranked it number 3 or 4 on the 5-point scale of importance used in the survey. Although China was ranked as the number 1 planned destination for new R&D, respondents to the survey expressed concern about the level of IP protection there. Along with IP concerns, 51 percent of the respondents said attracting top R&D talent was very important or critical, ranking it number 4 or 5. Other important challenges were identified: effective collaboration between international teams and compressing the time to commercialization.

4.4.1 Export Regulations

Even if corporations and universities are able to work out arrangements for the protection of the intellectual property and are able to enforce those agreements, a dampening effect on international collaborations will be that of export control regulations of the U.S. government. *Globalization of Materials R&D* summarizes the situation as follows:[13]

> The primary sources of export regulation—the Department of State's International Traffic in Arms Regulations (ITAR) and the Department of Commerce's Export Administration Regulations (EAR)—are considered by some in industry as a barrier to the global conduct of business. To compete in the global market and maintain a comparative advantage, U.S. industry must have access to both domestic and foreign technology, and manufacturing and export controls could be considered as hindering this access. Critics of the current export regulation regime maintain that foreign companies are executing contracts while U.S. companies are still seeking regulatory approval.
>
> Over the past 20 years most congressional activity on the export regimes has been to add sanctions and restrictions rather than to substantively review the underlying statutes. . . .
>
> *International Traffic in Arms Regulations*
>
> ITAR applies to items on the Munitions Control List—that is, to military end items, components, and the underlying technical data. In all cases a license or other authority is required prior to any export. . . . Approval is by no means assured and may be accompanied by conditions and limitations. The result is that where export approval is required, U.S. industry can find itself unable to plan with certainty, because there is no way of knowing when approval may be granted or how the license provisos may impact planned performance. . . .
>
> While ITAR is clearly critical for protecting the nation's interests in the systems and knowledge it covers, the ITAR regime can lead to schedule uncertainties, cumbersome

[12] Ibid., pp. 46-47.
[13] Ibid., pp. 95-97.

regulatory requirements, and compliance risks that inhibit international collaboration with U.S. suppliers and partners.[14]

Export Administration Regulations

EAR applies to commercial and dual-use commodities and their materials, components, software, and technology. . . .

The underlying statutory authority, the Export Administration Act, dates back to 1979. . . . The 2003 attempt to pass legislation failed in large part because it was deemed to not sufficiently strengthen national security controls on exports. As a result, the Department of Commerce is working to increase administrative controls on knowledge/technology transfer and exports. Critics say that the EAR impedes the collaborative efforts necessary for the conduct of global R&D.

4.4.2 The ITAR Fundamental Research Exclusion

In 1999 all space satellites were placed on the United States Munitions List (USML) and thereby were subject to the U.S. Department of State's International Traffic in Arms Regulations (ITAR). This ITAR designation had a chilling effect on university space research because it required ITAR licenses for scientific satellites and associated hardware as well as for technical data. In an effort to mitigate the resulting averse effects on university space research, the State Department amended ITAR requirements to exempt U.S. universities from the need to obtain ITAR licenses for fundamental research activities. Fundamental research was defined as "basic and applied research in science and engineering where the resulting information is ordinarily published and shared broadly within the scientific community."[15]

Despite this apparent regulatory relief, generally the space science community remained unclear about the dictates of ITAR requirements. For example, university researchers were confused about the publication requirements cited in the definition of "fundamental research" and uncertain about the implications for collaborative scientific research with companies and national laboratories—which were not covered by the fundamental research exclusion. Risk aversion regarding even unintentional ITAR infraction is understandable given the potential for criminal penalties.

As a consequence of the general climate of confusion and uncertainty over ITAR, the Space Studies Board of the National Research Council convened a workshop in 2007, with participants from academia, industry, and government.

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[14] Indeed, many foreign companies resist U.S. content, going so far as to advertise "ITAR-free" products. [Note: This footnote was added in the current writing and did not appear in the original quoted text.]

[15] U.S. Congress, International Traffic in Arms Regulations, Section 120.11 (8), April 1, 2007, Washington, D.C.

The workshop focused on ITAR requirements as they pertain to space science fundamental research. Issues addressed by the workshop nonetheless have relevance for other scientific and engineering disciplines, including materials science and engineering. Among the many ITAR issues covered during the 2007 workshop were the following:[16]

- The Department of State does not provide general guidance to help academic researchers understand ITAR requirements; all decisions are made on a case-by-case basis.
- Both students and university professors are dissuaded from pursuing careers in research areas that are encumbered by ITAR.
- University professors limit instruction for ITAR-related topics owing to uncertainty about regulation requirements, particularly in the presence of foreign students.
- Compliance with ITAR imposes a high cost on universities.
- ITAR hampers university-industry basic science collaboration because the fundamental research exclusion applies only to universities.
- Universities involved in international research formulate suboptimal research plans that limit information exchange in order to mitigate ITAR risks.
- ITAR-imposed obstacles induce potential international partners to seek alternative foreign research collaborators, such as in China, Russia, and India.

The insertion of scientific satellites into the United States Munitions List and the ensuing uncertainties surrounding the fundamental research exclusion have had significant impact on university space science research because of their broad, all-encompassing impact on the discipline. Without question, the fundamental research exclusion has had significantly less impact on the materials science and engineering university community. However, many of the concerns, uncertainties, and issues of confusion expressed during the Space Studies Board's ITAR workshop in 2007 are also applicable to materials research.

Industry-university collaboration under federally funded aerospace materials research programs typically involves the flow-down of ITAR-related contractual terms and conditions when the program involves materials and processes listed on the USML. Because researchers recognize the "open" nature of technical exchange among students within their laboratories (often involving non-U.S. persons), they are reluctant to engage in such research. University contract administrators have similar concerns, leading in some cases to a refusal to collaborate on such ITAR-controlled programs.

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[16] National Research Council. 2008. *Space Science and the International Traffic in Arms Regulations: Summary of a Workshop.* Washington, D.C.: The National Academies Press.

Significant global investment in materials technologies has led to a highly competitive global environment. Future access to world-class foreign propulsion materials technology may be difficult or impossible to obtain, thereby impacting the U.S. ability to achieve advanced propulsion system capabilities.

Findings

Finding: Accelerated foreign materials science and engineering innovation and invention threaten U.S. dominance in propulsion materials technology.

Finding: Delays and uncertainties associated with ITAR requirements hamper and discourage international research collaboration for propulsion materials.

Recommendation

Recommendation: The U.S. State Department should reformulate the ITAR fundamental research exclusion to encompass all such research whether performed in academia, industry, or government. This exclusion should also apply to fundamental research activities encompassed within larger research programs that contain other ITAR-controlled elements.

4.4.3 Export Regulation and Technology Transfer

On the subject of technology transfer in relation to export regulations, observations made in the *Globalization of Materials R&D* report are worth repeating here:[17]

> Any transfer of technology or intellectual property typically occurs in one of two ways. The first is a one-way transfer by which the recipient organization is provided training, data, software, or some other intellectual property that enhances its knowledge and capabilities in a specific technological area. The second way is technology collaboration, a two-way transfer of technology in which the companies typically share intellectual property to develop a specific product or technology. In either case, since technology is being transferred out of the United States and into a foreign country, that technology or intellectual property may be subject to ITAR or EAR. . . .
>
> Either set of regulations (ITAR or EAR) can impact the extent to which a transfer or collaboration across borders takes place. . . .
>
> Even if a license is awarded, provisos or limitations are usually placed on the offset activity that can greatly constrain the technology transfer or collaboration. These licenses and provisos can impede global research activities by inhibiting the necessary sharing of intellectual property and results of the research with those in the collaboration.

[17] National Research Council. 2005. *Globalization of Materials R&D: Time for a National Strategy.* Washington, D.C.: The National Academies Press, p. 97.

4.5 INTELLECTUAL PROPERTY PROTECTION MECHANISMS

The various intellectual property protection mechanisms that may be operative within an alliance or consortium vary depending on classification. In addition, the type of competition between various stakeholders, such as competitive, precompetitive, or cooperative, will impact the IP protection structure. Representative IP protection mechanisms that have been applied with success include government property rights (GPRs), nondisclosure agreements (NDAs), ITAR, patents (PAs), collaborative agreements (CAs), and Export Administration Regulations (EAR).

A representative set of alliances and/or consortiums that may be formed in response to the declining environment of support for propulsion materials R&D is summarized in the Table 4.1. Table 4.1 shows how the various IP protection mechanisms may be used to support alliances and consortiums, thereby generating more R&D opportunities.

Such alliances and consortiums enable the acceleration of the development of propulsion materials. This acceleration is due to the opportunities to benefit from relationships in which new and useful ideas, concepts, processes, and practices are made accessible to the U.S. military and industry. The U.S. export controls constraints ensure the prevention of an outflow of critical data.

4.5.1 Findings

Finding: Adequate intellectual property protection mechanisms exist.

Finding: Existing IP protection mechanisms within export controls are being used to develop and maintain alliances and consortiums that benefit U.S. structural propulsion materials and process R&D.

TABLE 4.1 Intellectual Property Protection Mechanisms for Various Types of Alliances and Consortiums

Type of Alliance or Consortium	U.S. Only	International Partners
Industry-Industry	CA, PA	ITAR, CA, PA
Industry-University	CA, PA, NDA, ITAR	ITAR, CA, PA
Industry-Government	CA, GPR, PA, NDA	ITAR, CA, PA, GPR, NDA
Government-University	CA, PA, NDA, ITAR	ITAR, CA, PA, NDA
Industry-Government-University	CA, PA, GPR, ITAR, NDA	ITAR, CA, PA, GPR, NDA

NOTE: Acronyms are defined in Appendix F.

4.5.2 Recommendations

Recommendation: DOD funding agencies should identify and support, both financially and through regulatory and administrative relief, opportunities for pre-competitive collaborative research for structural propulsion materials, both domestically and with global partners.

Recommendation: For the special case of pre-competitive research with global partners, the DOD, the Department of State, and other U.S. government entities, including the Department of Commerce, should proactively encourage such pre-competitive research opportunities and develop ways to facilitate knowledge transfer within wide, acceptable boundaries.

5

Elements of an Effective R&D Strategy

5.1 INTRODUCTION

Included in the charge to this committee was the key question, "Is the present strategy regarding development of new structural materials for propulsion the proper strategy?" (See Appendix A for the full statement of task.)

The direct answer to this question is, No. As described in Chapter 2, this study included an effort to identify the historic process followed for the development of new materials; it was found that there really has never been a single process. Yet, because of the emphasis on materials needed to bring jet and rocket engines out of their infancy after World War II, enormous strides in efficiency and performance were made. These advances all essentially tracked breakthroughs in materials properties and manufacturing processes. Enormous competition among companies gave rise to large materials groups in engine companies and the proliferation of suppliers, facilities, and—because of the demand for graduates in materials science and engineering—responsive programs in U.S. universities. Industry research and development (IR&D) programs within the companies seized on new innovations and ideas coming from within and occasionally coming from universities, which often had ties to the industry if only through their graduates. Performance continued to increase rapidly in metals, alloys, and processes owing to relatively easy development programs that were based on clear paths; however, the curve began to become asymptotic as evolutionary changes in materials no longer led to revolutionary increases in performance.

By the 1980s it was becoming clear that the approach to advancing performance that existed during the "engine wars" needed to be organized and directed in order to make the harder-to-discover advances in materials and processes. Some of this direction came in the form of large programs such as the National Aerospace Plane (NASP) and the High Speed Civil Transport (HSCT) Programs but was most successful in the long-term, stable funding environment of the Integrated High Performance Turbine Engine Technology (IHPTET) Program and its concomitant materials development support programs in the Air Force Research Laboratory (AFRL) and the Navy.

IHPTET's structural materials advances did not start from scratch, however. Promising materials candidates identified in the NASP Program, and continued through the High Speed Civil Transport–Enabling Propulsion Materials (HSCT-EPM) Program (a stable, modestly funded program), ensured a stream of viable materials candidates at the high 6.2 technology readiness level (TRL). Also, IHPTET was created when considerable talent and facility capabilities, left over from the engine-war years, still existed. A "feeder" program that matures fundamental discoveries to high 6.2 TRLs no longer exists (see the discussion in Chapter 2), and talent has been diffused and facilities decommissioned. In addition, the development time to mature fundamental discoveries to high 6.2-level materials candidates has changed little, whereas the time required for engine development has decreased owing to the use of integrated product development teams and computational methods. The fact is that even if a new IHPTET-like materials-development program were linked to a long-term, stable engine-demonstration program, there are few materials candidates remaining to mature. Nevertheless, the successes of the IHPTET Program created a mind-set within both the Materials and Manufacturing Directorate and the Propulsion and Power Directorate of the AFRL that led to the materials development plan addressed in Chapter 3 and discussed below in Section 5.2.

It is no surprise, then, that the three critical characteristics of a successful materials development program identified by the Materials and Manufacturing Directorate, as discussed in Section 3.6 of this report, primarily concern programs associated with engine development programs, with no real emphasis on stable, ongoing research directed at advancing 6.1 materials and processes to the high 6.2 TRLs required to feed such a program should it materialize. In fact, there seems to be no organization within the AFRL concerned with transition programs; the Air Force Office of Scientific Research (AFOSR), charged with funding all discovery research in the Air Force, places essentially all of its attention on research with "20-year horizons" and has virtually no concern about where its funded efforts go after a 6.1 program ends. In fairness to the AFOSR, its organizational mind-set, like that of the Materials and Manufacturing Directorate, was formed during a time when talent, facilities, and resources for transition work were abundant and transition programs were taking place in and outside the government. To the committee this presents a most disturbing realization: virtually no attention has been paid to some sort of follow-on to NASA's HSCT-EPM Program, nor does there appear to be any provision for funding such a program at the national level, either inside or outside the Department of Defense (DOD). It is worth noting that Donald C. Daniel in a 2006 National Defense University report[1] voices a similar alarm in a plea for rebalancing funding throughout the 6.1, 6.2, and 6.3 science and technology spectrum. Apart from the committee's concern about transition programs, his concern was that 6.3 funding was overemphasized at the expense of 6.1 funding. However, Daniel did specifically single out materials as one of the critical technical areas. In a sense, the committee has the same concern, that plans overemphasize the 6.3 end of the spectrum while not seeming to take into account that the 6.2 portion of the spectrum appears to have atrophied.

In this context, the chapter recommends approaches to address this concern. The fact is that the infrastructural environment for the development of new advanced structural materials for propulsion that existed in the past no longer exists. New strategies must be adapted not only for dealing with the infrastructure, but also for facing the reality that major thrusts for new engines are not likely to reappear in the foreseeable future, although history tells us that the need for new materials and processes must continue, if only to provide increased-performance engines to accommodate mission changes on existing aircraft and new challenges in fuel efficiency.

The following sections provide suggestions with respect to what might be done, but the strong recommendation of the committee is that *something* needs to be done.

5.2 ELEMENTS OF AN EFFECTIVE STRATEGY

The closest thing to a structural materials development "strategy" that the committee found in its study is the joint Advanced Materials Development Plan of the Materials and Manufacturing and the Propulsion and Power Directorates discussed in Chapter 3. That plan does an excellent job in identifying many structural materials advances required for future Air Force propulsion systems. It ties these to the relevant Focused Long Term Challenges (FLTCs), the challenges that guide AFRL's research and development (R&D) efforts. In this sense, the directorates' plan provides an excellent set of near- to mid-term objectives that are needed as part of any strategy. However, as pointed out previously, the plan assumes that the lack of feeder programs and the decline in the development environment

[1] Donald C. Daniel. 2006. *Issues in Air Force Science and Technology Funding,* Washington, D.C.: Center for Technology and National Security Policy, National Defense University, February.

are outside its purview. The roadmaps contained in the directorates' plan make tangential reference to the lack of feeder programs by identifying required developments, which fall on the roadmaps as unfunded lines with appropriately long timelines estimated for maturing a particular contribution. But to call this plan of the directorates a national strategy is to misunderstand the difference between, on the one hand, an execution plan that presumes all of the supporting infusion of technology and, on the other hand, a comprehensive strategy that encompasses the entire structural materials infrastructure that must be assembled in order to execute a plan.

This observation leads to the essence of what constitutes the rest of this chapter and provides a response to one of the tasks assigned to this committee: "Describe the general elements of an R&D strategy to develop materials for future military aerospace propulsion systems" (see Appendix A).

In this context, the use of the word "strategy" involves more than just the plan of the directorates; it includes the identification and support of all of the elements that may be outside this plan but that are necessary to the achievement of its overall goals. Elements of a strategy are discussed below and synthesized into 10 short recommendations at the end of this chapter that flow from the findings in the preceding chapters and from the discussion below.

As noted in preceding chapters, the processes used in previous decades for materials development no longer work. Those processes relied on a number of factors that no longer exist and realistically could not be sustained. In short, the environment has changed significantly in terms of funding, programs, partnerships, and the roles of industry and academia and the globalization of research and technology.

The past saw the sudden appearance of large but short-term materials development programs, associated with the NASP Program, for example, that provided substantial injections of technology into the development pipeline. But the continued progress of these technologies required individual champions who nurtured the technology through lean times and were astute about how to take advantage of flush times: materials that continued to mature through roller-coaster funding profiles required a personality-driven champion. Any national strategy may involve champions, but their existence, if they are needed, should be structural and driven by requirements.

The characteristics that should be part of a national strategy for developing advanced structural materials to meet evolving Air Force capability requirements are listed below and discussed individually in the succeeding sections:

1. Annual reviews of the Air Force propulsion materials requirements, objectives, and execution plans to adjust for budget changes and the external environment.

2. Better integration of AFOSR programs into Air Force propulsion materials plans and more involvement of academia and industry in the development of the plans.
3. The development of a stable, long-term materials development program that covers basic research through manufacturing and provides for materials insertion into test engines.
4. The development of a sufficiently robust and, most important, a stable funding stream.
5. The continued development of Integrated Computational Materials Engineering (ICME) approaches that promise to shorten the materials development time.
6. The implementation of a systems engineering approach to propulsion materials development that includes a risk management plan aimed at inserting materials considerations early in any engine development program.
7. The use of existing engines and demonstrators to expedite materials insertion and technology maturation.
8. The inclusion of academia in transition R&D both to take advantage of talent and facilities that exist at selected universities around the country and to ensure the development of the required workforce.
9. The increased use of government-industry-academia partnerships to conduct pre-competitive R&D.
10. The integration of foreign technology development and research with U.S. efforts. Opportunities for collaborative fundamental research should be pursued.

5.2.1 Regular Directorate Reviews of Propulsion Materials Requirements, Objectives, and Execution Plans

The environment in which technology is developed has changed dramatically over the years, and it will continue to change with the ongoing globalization of society and of economies. It is thus important to review and amend the propulsion materials plan, such as the one developed jointly by the AFRL directorates, on a regular basis. Although, as the committee has stated throughout this report, this plan is not by itself a strategy, a national strategy must include within it such a plan. Since flexibility is key in responding to changes, plan reviews should particularly emphasize the impact of changes in funding, making it clear how unfunded feeder programs will affect individual developments and timelines. Adjusted priorities should then be established to ensure that critical technologies advance in maturity. The evolving documents should ensure that the need for and benefits of new and advanced materials are clearly stated, since these documents are likely to be read by continually changing personnel in the roles of fund managers and decision makers.

5.2.2 Integration of AFOSR Programs into Overall Propulsion Materials Plan

The Air Force Office of Scientific Research is specifically charged with overseeing all 6.1 research funded by the Air Force. A critical role within this charge is that of finding and funding the newest and most innovative ideas for research in materials. Choosing which of these to fund is tied to future Air Force needs and, as pointed out in Chapter 2, having AFRL input into these choices is already written into AFOSR's mission statement. However, it is clear from the committee's investigation that cooperation, at least in the propulsion materials area, between the AFOSR and the AFRL directorates is tenuous and should be strengthened. At present AFOSR's focus is exclusively on the discovery of new materials with possible long-term implications (20-year horizons), with a limited focus on transition. It seems to the committee that AFOSR's portfolio should be more balanced, with at least some portion tied to nearer-term needs. Despite the long-term focus of the majority of AFOSR's portfolio, some mechanism (and adequate resources) must be found for making 6.1 program managers aware of the need for transitioning these to 6.2 efforts, and 6.2 efforts are the responsibilities of the AFRL directorates. One way to do this is to involve AFOSR program managers in the development and review of the Advanced Materials Development Plan.

Perhaps, however, the entire model of AFOSR independence should be reinvestigated. Reference has been made in this report to examples of rapid technical progress achieved through close interaction across research at all levels (TRL 6.1 through TRL 6.4), with the need for infusion of 6.1 basic science discovered in attempts at moving selected materials forward. In these examples, the AFOSR was a close cooperating participant in the advanced effort. Such cooperation, which did not hinder AFOSR's continued support for other long-term projects, could not help but influence the program manager's view of what the Air Force's long-term goals really were and what sorts of new discoveries were needed.

5.2.3 Development of a Stable, Long-Term Materials Development Program

Most of the advanced materials being used in engines today or being planned for near-term insertion are the result of long-sustained materials development programs such as HSCT-EPM. These programs no longer exist, and the materials that matured to high 6.2 TRLs as a result of these programs are now the only materials candidates available for consideration for insertion into new engines or development engines under the Versatile Affordable Advanced Turbine Engine (VAATE) Program. Without the replacement of a materials development program such as the HSCT-EPM Program, there will be no more advanced materials candidates for insertion into new propulsion systems.

There are numerous approaches to creating a new feeder program. It is not the committee's intention to suggest the exact form that it should take. Whatever the form, it is important that the elements of a successful program as discussed in Chapter 2 be included. While it is important that clear requirements are defined to aid in the selection of 6.1 candidates for maturation and process development, these requirements need not be tied to specific engine developments. In fact, history tells us that similar requirements exist for a number of capability goals; for example, the need for high-temperature materials in the last stages of a compressor is just as applicable to high-Mach-number, high-performance aircraft engines as it is to lower-Mach-number, high-efficiency aircraft engines. In the first case, the final compressor temperatures are produced by a combination of high-Mach-number ram recovery and moderate compressor pressure ratios, and in the second case by high compressor pressure ratios. Thus, these requirements should be developed not only on the basis of the requirement of a specific type of engine, but also on the basis of well-informed projections of materials needs applicable to any number of capabilities that exist or may become important at some future date.

The development of these well-informed requirements should be the product of a comprehensive study. The requirements should be reviewed at regular intervals to capture changing needs. A materials development strategy should be almost independent of the need for a new-engine development. A stable, long-term funding environment for transition programs is essential and of critical importance; see the separate discussion of the topic in Section 5.2.4.

In any long-term program, regular reviews of progress are critical. During such reviews, materials and processes that promise large impacts on requirements should be identified for enhanced funding, whereas others are identified to be maintained at lower levels that will enable invigoration at a later date. The process of making such down-selections should be sufficiently critical that it recognizes candidates no longer warranting continued development.

5.2.4 Development of a Stable, Sufficiently Robust Funding Stream

It cannot be overemphasized that, as stated earlier, stable, known, long-term funding, at whatever level, is critical to the success of a materials development program. This funding stream must be robust in being not only sufficient for the forecasted needs but also consistent over time. Charles Stevens[2] pointed out that roller-coaster funding profiles are far less productive than smaller amounts of overall funding that are sustained and stable. Cyclical funding that is unstable and varies greatly from year to year is highly detrimental, resulting in poorly planned and executed programs, duplication and re-creation of technology, waste, and loss of expertise.

[2] Personal communication, Charles Stevens, AFRL Propulsion and Power Directorate, July 20, 2009.

The funding stream for supporting whatever form the recommended materials development program takes must be stable and predictable over years. This does not mean that funding cannot vary, just that variations need to be coordinated with the plan, and that the plan itself may need to change. Funding levels and stability are determined at high levels in the government and depend on the current economic and political climate. Because the level of funding cannot be controlled at the level of researcher and user, what must be controlled is the response to changing funding levels. This requires that the projected spending plan be flexible and have options for increased and decreased funding levels. Spending money on poorly planned or inappropriate tests can be just as deleterious to the overall health of a materials effort as the loss of knowledge and skills associated with sudden and unplanned reductions. It is equally important that the strategies for the wise use of windfalls and the retention of knowledge and materials options once these funds end be part of an overall national strategy.

5.2.5 Continued Development of Computational Approaches to Shorten Materials Development Time

As already discussed, the time to develop materials to the point of insertion remains long compared to the development time for a new engine. Although the committee believes it critical to re-create a stable, long-term materials transition program to keep materials progressing into high 6.2 levels so that there is a pool of candidates closer to being ready for use, approaches to shorten the overall materials development cycle are still needed. Integrated Computational Materials Engineering has been developing rapidly over the past few years and will continue to do so as computational power increases further. Universities have been the home for this sort of development, and university research in this area needs to continue to be supported. Although not yet realized, ICME offers the potential to decrease development time significantly as well as to tailor materials with specific properties and to reduce the number, complexity, and time required for materials characterization and validation. ICME should be an integral part of the propulsion materials development program.

5.2.6 Implementation of a Systems Engineering Approach to Propulsion Materials Development

The development of advanced materials is necessary but not sufficient to provide the propulsion materials of the future. A systems-oriented approach is required. It is necessary to have a detailed understanding of the operational environment of potential future engines, and it is equally important to maintain a close interaction among all participants in the engine- and materials-development processes. Specific engine designs and operating parameters will not be available early in the materials development process, but a combined team must understand the range of requirements and bring to bear all of the necessary systems engineering techniques, including requirements analysis, allocation, system modeling and simulation, testing and evaluation, and others, and must also understand manufacturing and sustainability constraints.

5.2.7 Use of Existing Engines and Demonstrators to Expedite Materials Insertion and Technology Maturation

Although the committee has emphasized as a primary concern the demise of feeder programs, it is important to continue to make progress as well on the 6.3 efforts and beyond. In briefings and communications to the committee, much concern with respect to maturing technology at the higher levels was voiced by AFRL directorate personnel because of the decline in the number of demonstrator engines into which new-materials components could be inserted. In the present climate, however, it is not likely that a dedicated new engine-demonstrator program is likely to appear suddenly. It is thus imperative that innovative ways be developed to take advantage of existing engine testbeds. Also, some accommodation to allow for risk in expanding the usefulness of future demonstrators for the testing of new-materials components should continue to be explored. As the committee has pointed out, new engines will be needed in the future and, before that, continued spiral improvements in existing engines; thus, using existing engines that can be made available to test new components should be considered as the primary path for bringing new manufacturing approaches and new materials insertion candidates to maturity.

5.2.8 Inclusion of Academia in Transition Research and Development

Closer ties among academia, industry, and the AFRL may be able to compensate for some of the continuing decline in the materials and processes research environment in the United States. Such ties might make use of the talent and facilities available in academia for more focused materials and processes research efforts and also help develop a workforce with the appropriate skills and knowledge to pursue related materials development in industry and government. These closer ties will necessarily require coordination and cooperation between the AFOSR and the AFRL, but under the present structure and funding levels, one can expect that adding these goals to existing programs will have only marginal impact.

A possible approach that might be considered is a consortium arrangement involving the DOD, academia, and industry, and perhaps NASA, similar to the approach taken by DOD's Joint Technology Office for Directed Energy, which has advanced many of the technologies associated with directed energy weapons. In Joint Technology Office (JTO)-sponsored programs, universities have demonstrated that their research products can have impact on DOD development programs at the 6.3 level and beyond.

In setting up such a consortium arrangement, it would be important to be cognizant of the fact that some AFRL and industry researchers consider university research as "sandbox efforts," and their attitude is generally that the main role of universities is only to provide a stream of graduates. There also seems to be a misconception that only 6.1 efforts can be performed at universities. In fact a number of universities are integral to industry and government development programs. It is also not the case that universities can only work on low-TRL or 6.1 programs; it is increasingly common for some universities to be involved in 6.2-funded programs and beyond. For example, the charter of the University of Notre Dame's Institute of Flow Physics and Control (FlowPAC) specifically mentions that the institute's research will cover R&D programs that range from fundamental to applied research. The fact that applied research takes place in FlowPAC makes research personnel there more aware of how and where products of their fundamental research programs might be transitioned into development programs.

The committee encourages organizations charged with the development of advanced structural materials to consider developing some sort of consortium program that attempts to link academia, government, and industry. Such a program could help to bridge any number of shortfalls identified by this study. These shortfalls include the realities of contracting for the availability of research infrastructure. There exist within industry, government, and academia facilities that might be able to be used to test components in near-engine environments. These facilities might be included as part of a consortium that would allow widespread sharing of knowledge at the pre-competitive level. Such a consortium should also allow for the partnering of industry and academia in proprietary agreements that would not be shared with the consortium at large, but could still make use of the shared facilities. It seems essential that a steering committee be part of this type of consortium and oversee its efforts. The steering committee should be made up of AFRL directorate personnel and the AFOSR program managers overseeing the materials area. Among other benefits of such an arrangement, the participation of AFOSR program managers would make them more aware of all of the issues in maturing technology, including process development, thereby providing a mechanism for alleviating the concerns about the AFOSR discussed in Section 5.2.2.

5.2.9 Development and Increased Use of Partnerships

Partnerships Within the Department of Defense and with Other Government Agencies

A major part of a strategy for developing advanced structural materials should be to partner with other funding agencies within and outside the DOD. NASA was a major player in the materials developments of the 1990s. Although NASA has moved away from basic research to some extent in recent years, there continues to be collaboration between the Air Force and NASA in the area of hypersonics. Whoever the partner, it is important that the Air Force coordinate the materials development program with others. It should also be noted that the Air Force has needs for materials other than propulsion materials, and that at low TRLs there should be synergies with other Air Force programs. Partnerships and collaborations should mean that all the partners have a stake in materials of interest to them, and although the focus at individual agencies will be on their priorities or strengths, it should not mean that effort is conducted at only one agency.

The ongoing Defense Science and Technology Reliance 21 Materials and Processes Program, set up to coordinate efforts between DOD agencies, has been somewhat effective. In such a coordination program the emphasis is usually directed toward minimizing duplication, but care should also be taken to emphasize cooperation and taking advantage of synergies in R&D efforts. Additionally, rather than just eliminating infrastructure at one facility in favor of another, it is important to consider sharing with other communities working on similar problems. Such cross-pollination and competition help maintain technical excellence and promote innovation and revolutionary as well as evolutionary advances. This type of coordination between agencies must become part of the strategy for the development of propulsion materials.

Development of Partnerships with Industry

Just as partnerships within the government laboratories are critical to the success of materials development, so also are partnerships with industry, which has been an active participant in previous materials development programs. Although R&D within industry has decreased and become more focused on specific needs, industrial partnership is essential if materials are to be manufactured in a robust, cost-effective manner, and then to be tested and evaluated in the most cost-effective manner, and finally to be transitioned into specific technologies. The infusion or adaptation of commercial technology to government needs should be another part of the strategy, ensuring that the Air Force is taking advantage of all possible sources for the technology that it needs in order to maintain leadership in propulsion. The discussion in Chapter 4 indicates that intellectual property rights, which are always an issue when involving industry, have been and can be worked out to the satisfaction and benefit of all parties. In this regard, the identification and support of pre-competitive research are essential to the success of a strategy that seeks to leverage industry participation.

5.2.10 Integration of Foreign Technology Development and Research with U.S. Efforts

Globalization presents new challenges when it comes to attempting to maintain U.S. leadership in propulsion materials. Globalization has changed the technical development and knowledge environment to the point that the United States must consider different paradigms for staying on the leading edge. No longer can this nation expect to develop all of the required technology domestically and to retain that knowledge. Instead, the United States must consider ways to obtain knowledge and expertise from other countries and must become expert at adapting and synthesizing that knowledge into the leading-edge technologies that are required. Collaboration with foreign entities will become increasingly important; however, U.S. and foreign approaches to the protection of others' intellectual property (IP) are often different, and foreign approaches do not provide adequate safeguards, leading to legitimate concerns by companies. Also, although the International Traffic in Arms Regulations (ITAR) and other export control laws have successfully protected U.S. technology, they often serve as a barrier to collaboration and to the full leveraging of foreign technology. Ways will have to be found to adequately implement and enforce existing legal safeguards for IP, innovative approaches to the sharing of IP will need to be considered, and the U.S. government will need to provide more clarity and more efficient application of ITAR and of export control laws.

5.3 RISK MANAGEMENT

The comments presented in this section cut across many of the topics covered above. However, since risk management has been an important contributor to de-emphasizing new materials in the VAATE Program, it is addressed separately here.

Risk aversion by program managers has increased as funds have become tighter and the consequences of failures have become more severe. Risk aversion in terms of materials usually manifests itself in the decision to use a material that is already proven in some other applications or that has been extensively tested. Generating the amount of data required to qualify a material for an application is expensive and daunting.

Managing risk involves reducing risk by developing and advancing materials early, and planning for risk in programs; in both cases the need for materials development at an early stage is clear. A successful strategy, therefore, needs to include an understanding of materials maturity and a plan for providing materials at higher TRLs to the materials development projects in order to increase the materials chances of insertion. The benefits of a new technology clearly must far outweigh the risks; the materials development program has to define the benefits in a qualitative manner while reducing the risk. A program that goes past 6.2 into 6.3 or 6.4 development should be part of the strategy, as should the use of more sophisticated computation and modeling to reduce the amount of testing and validation of materials needed in order to move the materials to levels of risk acceptable to engine developers.

All programs at whatever TRL should have a risk management plan. The plan can identify areas where additional funding, time, or partnerships are needed. Identifying risks and approaches for minimizing them is a major tool for development planning and will increase the likelihood of materials candidates being tested in the first place and the success of eventual insertion. Risk planning is a critical step in developing the path from 6.1 research to use in a system. Financial risk is also an issue, and early partnering with industry to develop manufacturing techniques that are cost-effective and robust is integral to the strategy.

5.4 RECOMMENDATIONS

Recommendation: The Air Force Research Laboratory's Materials and Manufacturing Directorate and Propulsion and Power Directorate need to develop a strategy to maintain or regain U.S. preeminence in propulsion materials. The strategy should include the regular review and updating of the directorates' propulsion materials plan, with an emphasis on the consequences of unfunded items, the changing external environment, and maintaining a balance for the near-, mid-, and far-term activities in response to the Focused Long Term Challenges and funding commitment.

Recommendation: The strategy for developing future aerospace propulsion materials should define a materials development program with stable and long-term funding. The program should cover basic 6.1 research through 6.3 development and include manufacturing and insertion strategies. It should involve industry, academia, and other government entities, and it should selectively consider global partners for pre-competitive collaboration. Essential elements of the strategy include a steering committee, feedback metrics, and a risk reduction plan based on systems engineering practices.

Recommendation: The AFRL's Materials and Manufacturing Directorate and Propulsion and Power Directorate should increase their communication and collaboration with the AFOSR, system program offices, industry, and academia relative to propulsion materials needs, advances, technology readiness, and the potential systems payoffs of technology insertion.

Recommendation: To maintain or regain the U.S. military competitive advantage in the areas of propulsion materials and to keep the United States on the leading edge of propulsion technology, there is a need for advocacy within the Office of the Secretary of Defense/Director, Defense Research and Engineering, to increase activities in new materials development and competitive 6.2 component and 6.3 demonstrator programs.

Recommendation: The U.S. State Department should reformulate the ITAR fundamental research exclusion to encompass all such research whether performed in academia, industry, or government. This exclusion should also apply to fundamental research activities encompassed within larger research programs that contain other ITAR-controlled elements.

Recommendation: DOD funding agencies should identify and support, both financially and through regulatory and administrative relief, opportunities for pre-competitive collaborative research for structural propulsion materials, both domestically and with global partners.

Recommendation: For the special case of pre-competitive research with global partners, the DOD, the Department of State, and other U.S. government entities, including the Department of Commerce, should proactively encourage such pre-competitive research opportunities and develop ways to facilitate knowledge transfer within wide, acceptable boundaries.

Recommendation: The research activities of the Air Force Office of Scientific Research should tie more closely to AFRL propulsion materials needs so as to provide a path to insertion. Together the AFOSR and the AFRL should develop a research portfolio that covers a wider range of near-, mid-, and far-term needs.

Recommendation: The United States should continue to develop computational methods to shorten materials development time and to reduce the time required for testing and materials validation so as to reduce the risk related to insertion of new materials.

Recommendation: The Air Force should fully implement the R&D strategy that it develops, and it should reevaluate its strategy annually.

Appendixes

A

Statement of Task

The committee will:

- Examine whether current and planned U.S. R&D efforts in materials for aerospace propulsion are sufficient (a) to meet U.S. military needs and (b) to keep the U.S. on the leading edge of propulsion technology.
- Consider mechanisms for the timely insertion of materials in propulsion systems and, if necessary, how these mechanisms might be improved.
- Consider mechanisms in place that retain intellectual property (IP) securely and how IP might be secured in future R&D programs.
- Describe the general elements of an R&D strategy to develop materials for future military aerospace propulsion systems.

The committee will consider both air breathing and self contained fuel/oxidizer systems including scramjet capabilities and take account of: (a) fuel-efficiency and materials-technology challenges at both subsonic and supersonic (up to Mach 5); (b) findings and recommendations in the recent NRC report entitled *A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs* issued in 2006; (c) the impact of current non-U.S. investments in propulsion materials technologies; (d) the lead time for insertion of new materials into aerospace propulsion technologies and what would it take to shorten the timeline, if it is too long; and (e) the evolution of U.S. R&D on materials for aerospace propulsion with due consideration of:

— Historic funding levels;
— Government agencies involved;
— Government investments (for both defense and civil applications) and industrial investments in propulsion R&D; and
— Outside drivers such as non-defense and non-NASA investments and needs.

B

The Leading Edge in Aerospace Propulsion

The Committee on Materials Needs and R&D Strategy for Future Military Aerospace Propulsion Systems analyzed the three most recent decades of top 10 affiliations (companies, universities, and government-affiliated institutions) for work done in the area of propulsion as indicated by searches of the keywords "Propulsion," "Hypersonic," "Scramjet," and "Supersonic" in publications listed in the Scopus database and in patents files in selected countries' patent offices. From this analysis, it is clear that the amount of public information in these fields of aerospace, propulsion-related work is increasing and that the dramatic lead once enjoyed by the United States no longer exists. Instead there is a more uniform distribution of efforts worldwide. What cannot be determined from this analysis is how much information is kept as trade secrets or what portion is driven by the need to "publish or perish" at universities. However, this analysis was performed on the body of commonly available knowledge. As such, in most cases it reflects the overall effort even though there might be a large unpublished body of knowledge as well. Clearly, it is also worth noting that the field of published information is no longer dominated by company-affiliated work; instead, universities and government-affiliated institutions are in the top 10 spots.

B.1 COMPARISON OF WORLDWIDE PUBLISHED AEROSPACE PROPULSION KNOWLEDGE

B.1.1 International Hypersonics and Scramjet Papers

With the help of the National Air and Space Intelligence Center (NASIC), a compilation was made of some of the international hypersonics and scramjet papers published by the American Institute of Aeronautics and Astronautics (AIAA) from 1995 to 2009.[1] The list in Table B.1 shows in alphabetical order some of the countries active in the aerospace propulsion area and the number of their publications related to both hypersonics and scramjet work that were analyzed by the committee. As can be seen, the most prolific countries (the United States not included) were China, France, and Russia. However, there might be certain topic areas or countries that have a tradition of publishing with AIAA, whereas others might not.

The following lists of the titles of hypersonics- and scramjet-related papers published from 1995 through 2009 are arranged alphabetically by country. In addition to the titles of papers from AIAA—indicated by "[AIAA]" at the end of the title—the lists show titles from the Institute of Electrical and Electronics Engineers (indicated by "[IEEE]")[2] and from the Institute for Scientific Information's Web of Knowledge listed publications (indicated by "[ISI]").[3]

Australia

- "Comparison of Computation and Measurements in a Supersonic Cavity Combustor" [AIAA]

China

- "Aerothermodynamics of the Waveriders Applying Artificially Blunted Leading Edge Concept" [AIAA]
- "Airframe/Scramjet Integrated Design of Hypersonic Cruise Vehicle" [AIAA]
- "Application of Taguchi Design Methods and Uniform Design Methods to Scramjet Propulsion System Optimization for Hypersonic Cruise Vehicle" [AIAA]
- "Modeling for Coupled Dynamics of Integrated Hypersonic Airbreathing Vehicle and Engine" [AIAA]

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[1] American Institute of Aeronautics and Astronautics, *Publications & Papers,* http://www.aiaa.org/content.cfm?pageid=2. Accessed November 3, 2010.

[2] *IEEE Xplore Digital Library*, http://ieeexplore.ieee.org/Xplore/guesthome.jsp. Accessed November 3, 2010.

[3] *ISI Web of Knowledge*, http://isiwebofknowledge.com/. Accessed November 3, 2010.

TABLE B.1 Analyzed Papers (non-U.S.) Published by AIAA, 1995-2009

Country	Number
Australia	1
China	12
France	10
Germany	5
India	5
Italy	4
Japan	8
Russia	10
Sweden	2

- “Oscillatory Flows of Rectangular Hypersonic Inlet Unstart Caused by Downstream Mass-Flow Choking” [AIAA]
- “Overall Performance Design of Ramjet for Combined Engine” [AIAA]
- “Parallel Numerical Investigation of Fuel Atomization and Combustion in a Scramjet” [AIAA]
- “Parameter Research of an MHD Controlled Inlet” [AIAA]
- “Research on Optimal Regulating Rule for Scramjet Control” [AIAA]
- “Research on Three-Dimensional Scramjet Inlet” [AIAA]
- “Study on Solid Rocket Based Wave-Rider Concept with Skipping Trajectory” [AIAA]
- “Thrust and Drag of a Scramjet Model with Different Combustor Geometries” [AIAA]

- “Catastrophe, Hysteresis and Bifurcation of Mode Transition in Scramjet Engines and Its Model” [ISI]
- “CFD Assessment of Classifications for Hypersonic Inlet Start/Unstart Phenomena” [ISI]
- “Development of Supersonic Scramjet Inlet” [ISI]
- “Hypersonic Combined Cycle Engine Concept with Tandem Layout” [ISI]
- “Integrated Aero-Propulsive CFD Analysis for 2D Air-Breathing Hypersonic Vehicle” [ISI]
- “Numerical Study on Self-Sustained Oscillation Characteristics of Cavity Flameholders in a Supersonic Flow” [ISI]
- “Preliminary Study on Hypersonic Airbreathing Engine Performance” [ISI]
- “Pyrolysis of Hydrocarbon Fuel ZH-100 Under Different Pressures” [ISI]

- "Trajectory Planning for Hypersonic Vehicle Using Improved Sparse A* Algorithm" [IEEE]

Following, in addition to the papers listed above from AIAA, ISI, and IEEE, are titles of Chinese hypersonic- and scramjet-related papers:[4]

- "Application of Resistance Heater in Supersonic Combustion Facility"
- "Cold Flow Research in Scramjet Combustor"
- "Combustion Mode Transition in a Scramjet Engine"
- "Conceptual Study on Integrated Design of Magnetohydrodynamic Bypass Scramjet for a Waverider-Based Hypersonic Vehicle"
- "The Coupling Model and Control Between Scramjet and Airframe for Hypersonic Vehicle"
- "Design and Analysis of Thermal Structure of Inlet of Scramjet"
- "Development of Supersonic Scramjet Inlet"
- "Effects of Scramjet Combustor Configuration on Combustor Performance"
- "Experiment on Control of Liquid Hydrocarbon Fueled Scramjet Combustor"
- "Influences of Geometric Parameters upon Nozzle Performances in Scramjets"
- "Investigation on Flow Pattern of Sidewall Compression Scramjet Inlet with Single Central Strut"
- "Multi-Objective Optimization Design of Airframe for Hypersonic Cruise Vehicle"
- "Numerical Investigation of Hydrogen Combustion-Heater for Scramjet Ground Test"
- "Numerical Simulation of Flaming Gas Generator with Catalytic Reforming Process"
- "Numerical Simulation of the Flow Field for Resistance Pressure in Scramjet Isolator"
- "Numerical Simulation on the Turbulent Flow Field of Supersonic Combustion"
- "One-Dimensional Evaluation of the Scramjet Flow Path Performance"
- "One New Type Closed Cooling Cycle of Scramjet"
- "Performance Analysis of MHD-Arc-Scramjet Combined Cycle Engine"
- "Performance Comparison Between 2-D Scramjet Inlet and 3-D Sidewall Compression Scramjet Inlet"
- "Study on Flow Characteristics of Scramjet Isolator"
- "3-D Numerical Investigation on Supersonic Combustion of Hydrogen in Two Different Types of Scramjet Combustors"

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[4] East View Information Services, *Online Databases*, http://online.eastview.com/login_china/index.jsp. Accessed November 4, 2010.

France

- "Air-Breathing Launch Vehicle Activities in France—The Last and the Next 20 Years" [AIAA]
- "Composite Technologies Development Status for Scramjet" [AIAA]
- "A Contribution to the Development of Actual Continuous Detonation Wave Engine" [AIAA]
- "First Steps for the Development and Testing of a Pulse Detonation Engine for UAV Application" [AIAA]
- "Improved Prediction of Heat Transfer in a Rocket Combustor for GOX/Kerosene" [AIAA]
- "Modal Linear Stability of the Near-Wall Flow on a Hypersonic Forebody" [AIAA]
- "Numerical Simulations and Experimental Results of Endothermic Fuel Reforming for Scramjet Cooling Application" [AIAA]
- "Scramjet Combustor Design in French PREPHA Program—Final Status in 1998" [AIAA]
- "Scramjet Combustor Design in France" [AIAA]
- "Systematic Numerical Study of the Supersonic Combustion in an Experimental Combustion Chamber" [AIAA]

- "Characterization of Coking Activity During Supercritical Hydrocarbon Pyrolysis" [ISI]
- "SFPG2007—Pyrolysis of Supercritical Endothermic Fuel: Evaluation for Active Cooling Instrumentation" [ISI]

Germany

- "Experimental Verification of Heat-Flux Mitigation by Electromagnetic Fields in Partially-Ionized-Argon Flows" [AIAA]
- "Influence of Heat Capacity Ratio on Pressure and Nozzle Flow of a Scramjet" [AIAA]
- "Investigation of the Performance of a Scramjet Inlet at Mach 6 with Boundary Layer Bleed" [AIAA]
- "Measurement of Flow Properties and Thrust on Scramjet Nozzle Using Pressure-Sensitive Paint" [AIAA]
- "Multidisciplinary Analysis and Evaluation of Supersonic Combustion Ramjets" [AIAA]

- "Constraining Heat Input by Trajectory Optimization for Minimum-Fuel Hypersonic Cruise" [ISI]

- "Measurement of Rotational Temperatures Near Surfaces in Hypersonic Flow" [IEEE]

India

- "Experimental Investigations on the Effect of a Thermal Bump in the Hypersonic Flow Around a Flat Plate" [AIAA]
- "Investigation of Missile-Shaped Body with Forward-Facing Cavity at Mach 8" [AIAA]
- "Shock Tunnel Studies on Drag Reduction of a Blunt Body Using Argon Plasmajet" [AIAA]
- "Studies on Unsteady Shock Interactions near a Generic Scramjet Inlet" [AIAA]
- "Trajectory Optimization and Guidance of an Air Breathing Hypersonic Vehicle" [AIAA]

- "Numerical Flow Visualization of a Single Expansion Ramp Nozzle with Hypersonic External Flow" [ISI]

Italy

- "Is the MHD Scramjet Really an Advantage?" [AIAA]
- "Optimization of Hybrid Sounding Rockets for Hypersonic Testing" [AIAA]
- "Sizing of TBCC Hypersonic Airbreathing Vehicles" [AIAA]
- "Supersonic Combustion Models Application in Advanced Propulsion Concepts" [AIAA]

- "Exergy Analysis of Hypersonic Propulsion Systems: Performance Comparison of Two Different Scramjet Configurations at Cruise Conditions" [ISI]

- "Hypersonic MHD Interaction on a Conical Test Body with a Hall Electrical Connection" [IEEE]
- "Magnetohydrodynamic Interaction in the Shock Layer of a Wedge in a Hypersonic Flow" [IEEE]
- "Numerical Modeling of MHD Interaction in the Boundary Layer of Hypersonic Flows" [IEEE]

Japan

- “Computational Analysis of HVEPS Scramjet MHD Power Generation” [AIAA]
- “Experimental Analysis of TSTO Aerodynamic Interactions Based on Oil Flow Patterns at Hypersonic Speed” [AIAA]
- “Mach 8 Ground Tests of the Hypermixer Scramjet for HyShot-IV Flight Experiment” [AIAA]
- “Measurement of Hypersonic Boundary Layer Transition on Cone Models in the Free-Piston Shock Tunnel HIEST” [AIAA]
- “Numerical Simulations in Scramjet Combustion with Boundary-Layer Bleeding” [AIAA]
- “Performances of a Rocket Chamber for the Combined-Cycle Engine at Various Conditions” [AIAA]
- “Payload to Low Earth Orbit’ [AIAA]
- “Problems of Numerical Diffusion Found in Scramjets” [AIAA]

- “An Analytical Study of Scramjet Combustion at Mach 6 Flight Conditions” [ISI]
- “Development Study of the Mach 6 Turbojet Engine” [ISI]
- “Frost Formation Problem in the Development of a Hypersonic Turbojet Engine” [ISI]

- “Temperature Measurement of Noble and Combustion Gas Plasmas with Optical Measurement System for MHD Generators” [IEEE]
- “Variable Nozzles for Aerodynamic Testing of Scramjet Engines” [IEEE]

Russia

- “Atmospheric Cruise Flight Challenges for Hypersonic Vehicles Under the Ajax Concept” [AIAA]
- “Hypersonic Technologies of Atmospheric Cruise Flight Under AJAX Concept” [AIAA]
- “Magnetohydrodynamic Control on Hypersonic Aircraft Under ‘Ajax’ Concept” [AIAA]
- “MHD Control by External and Internal Flows in Scramjet Under AJAX Concept” [AIAA]
- “Parametric and Numerical Investigations of Scramjet with MHD Bypass” [AIAA]
- “The Prospects of Hypersonic Engines In-Flight Testing Technology Development” [AIAA]

- "The Program for the Complex Investigation of the Hypersonic Flight Laboratory (HFL) 'IGLA' in the PGU of TSNIIMASH" [AIAA]
- "Scheme and Inlet Performance of Supersonic Business M = 1.6 Cruise Aircraft" [AIAA]
- "Scramjet with MHD Controlled Inlet" [AIAA]
- "Scramjet with MHD Bypass Under 'AJAX' Concept" [AIAA]
- "Experimental Study of Fuel/Air Mixing Using the Cavity in the Supersonic Flow" [AIAA]

- "Atmospheric Cruise Flight Challenges for Hypersonic Vehicles Under the Ajax Concept" [ISI]
- "Investigation of Self-Sustaining Waves in Metastable Systems: Deflagration-to-Detonation Transition" [ISI]
- "Shock-Wave Flow Regimes at Entry into the Diffuser of a Hypersonic Ramjet Engine: Influence of Physical Properties of the Gas Medium" [ISI]

- "Background and Prediction of Correct Full-Scale Reproduction in Wind Tunnels as Concerns Gas Dynamic Parameters of Hypervelocity Atmospheric Flights and Scramjet Combustion Chamber Conditions" [IEEE]
- "Mathematical Modeling of Supersonic Turbulent Separated Flows in the Vicinity of Forward- and Backward-Facing Steps" [IEEE]
- "Overview of EML Research in Russia" [IEEE]
- "Velocity Field Measurements in a Swirled Gas Flow by Thermal Imaging Technique" [IEEE]

Sweden

- "Concept Study for a Mach 6 Transport Aircraft" [AIAA]
- "System Analysis of High Speed, Long Range Weapon Systems" [AIAA]

Individual Countries' Research Efforts

Some countries have too few publications in this field to allow pinpointing where the research efforts lie; for some it is possible to give a broader overview. The work listed above for China is mostly related to a hypersonic cruise vehicle, combustors, inlets, and simulation of processes. For France a number of publications are related to detonation engines and scramjet combustors, whereas Germany and Italy seem to work on flow analysis. Japan has a set of publications indicating work on many aspects of high Mach flight. Finally, many of Russia's publications are related to the Ajax concept.

B.1.2 Foreign Patents in the Hypersonics Area

NASIC has compiled a list of foreign patents in the hypersonics area. The list below, by the country in which the patents are filed, shows the titles of some of these patents.[5] As can be seen, China is patenting inlet designs, whereas France is patenting ramjet engine designs. However, most of the foreign patents are filed in Russia, and they deal with most fields needed for understanding hypersonics and the scramjet.

China

- Ablation-Free Self-Adaptive Heat-Resistant and Damping System for High Supersonic Aerocraft
- Fixed Geometrical Supersonic-Speed and High Supersonic-Speed Adjusting Air Inlet
- Hypersonic Intake Duct Starting/Non-Starting Mode Integrated Classification and Determination Method
- Hypersonic Liquid Jet Generator
- Internal Waverider-Derived Hypersonic Inlet with Ordered Inlet and Outlet Shape and Design Method
- Reverse Pulse Explosion Heat-Resistant and Damping Method for High Supersonic Aerocraft

France

- Aircraft Ram Jet Engine for Supersonic and/or Hypersonic Flight
- Fuel Injection Device for Ramjets for Aircraft
- Ramjet Engine for Aircraft with Supersonic and/or Hypersonic Flying Speed
- Ramjet Engine for Supersonic or Hypersonic Aircraft
- Thermal Protection Structure, Especially for Components Subjected to Very High Temperatures, e.g., Hypersonic Aircraft Engines
- Variable Geometry Ramjet for Aircraft

Germany

- Low-Temperature High-Velocity Flame Spraying System
- Combined Supersonic/Hypersonic Combustion Ramjet Has Air Injector System for Reflection of Supersonic Intake Air

[5] Some of the information is available at European Patent Office, http://ep.espacenet.com/.

Japan

- Engine for Exhaust Nozzle for Hypersonic
- Engine for Hypersonic Transport Aircraft
- Stationary Detonation Combustor, and Stationary Detonation Wave Generating Method

Russia

- Construction of Hypersonic Projectile with Self-Pressuring Compressive Detonation Jet Engine Having High Working Pressure and Using High Explosive Charge for Propulsion
- Device for Stabilization of Supersonic Combustion
- Engine Plant of Hypersonic Craft
- Experimental Hypersonic Ramjet Engine
- Hybrid Air-Jet Magnetogasdynamic Engine
- Hypersonic Aircraft
- Hypersonic Aircraft Flight Control Method
- Hypersonic Chemical Reactor
- Hypersonic Cryogenic Air-Jet Engine
- Hypersonic Guided Missile
- Hypersonic Pulse Detonating Engine and Method of Its Functioning
- Hypersonic Ramjet Engine
- Member Separable from Hypersonic Flying Vehicle Possessing Aerodynamic Efficiency
- Method for Generating Electrical Energy Onboard Hypersonic Flying Vehicle and MHD Generator Used for the Purpose
- Method for Increasing the Hypersonic Speeds of Flow of Light Gases
- Method of Control of Aerodynamic Streamlining of Flying Vehicle and Plasma Generator
- Method of Control of Supersonic Air Flow over Aircraft
- Method of Determining Tractive Force of Hypersonic Direct Flow Aerojet Engine from Results of Flying Experiments in Hypersonic Flying Laboratories
- Method of Hypersonic Flow Preparation for Aerodynamic Research and Device for Its Implementation
- Method of Measuring Flight Thrust of Hypersonic Ramjet Engine of Unmanned Hypersonic Flying Laboratory
- Method of Organization of Detonation Combustion Chamber of Supersonic Ramjet Engine
- Method of the Heat-Mass-Power Exchange and a Device for Its Realization

- Methods of Determination of Attack Angles and Slide at Flight Trials of Supersonic Flying Machine
- Methods of Setting-Up Combustion in Hypersonic Ramjet Engine and Hypersonic Ramjet Engine for Realization of These Methods
- Propulsion System for Hypersonic Aircraft and Spacecraft

B.2 FURTHER COMPARISON OF WORLDWIDE PUBLISHED AEROSPACE PROPULSION KNOWLEDGE

Building on the NASIC-collected data, a follow-up was done by the committee using the Scopus database in order to look at a broader area than that represented by the previously discussed publications alone, and also to put the foreign publications in context with published work done in the United States at the same time.

Below is information related to certain keywords used for the search—"Propulsion," "Hypersonic," "Scramjet," and "Supersonic"—and how those are reflected in terms of the number of publications as a function of publication year as well as affiliation, with a special emphasis on the top 10 publication affiliations and each affiliation's country of origin for the three past decades: 1980-1989, 1990-1999, and 2000-2009. The information is also looked at with respect to the total publication production as a function of the top 10 publication venues (journals, conference proceedings, and so on) over the entire period. Data also include total patents from some of the key patent offices (the U.S. Patent Office, the European Patent Office, the World Intellectual Property Organization of the United Nations, and the patent offices of the United Kingdom and Japan). It is hoped that this analysis captures one view of where the leading edge of future aerospace propulsion knowledge is and where it is heading. Although this method of looking at published information is not optimal for determining the full level of aerospace propulsion activities, it is one of the few approaches that provide one form of hard numbers to compare. Even though it is possible to argue about the quality of the work from different institutions, these data do indicate where activity is going on, and usually that is an indication of where a rapid increase in knowledge and ability is taking place.

B.2.1 Publications and Patents Related to Keyword "Propulsion"

As can be seen in Figure B.1, there was a clear increase in the publication rate of propulsion-related documents in the early 2000s, from around 100 per year to almost 1,000 per year. As seen below, this type of increase is replicated in several of the subfields described in this appendix (hypersonics, scramjet, and supersonics), albeit with some differences. Some "temporary" increases in publication numbers can also be observed during the mid-1980s and early 1990s, preceding the "explosion" of recent years.

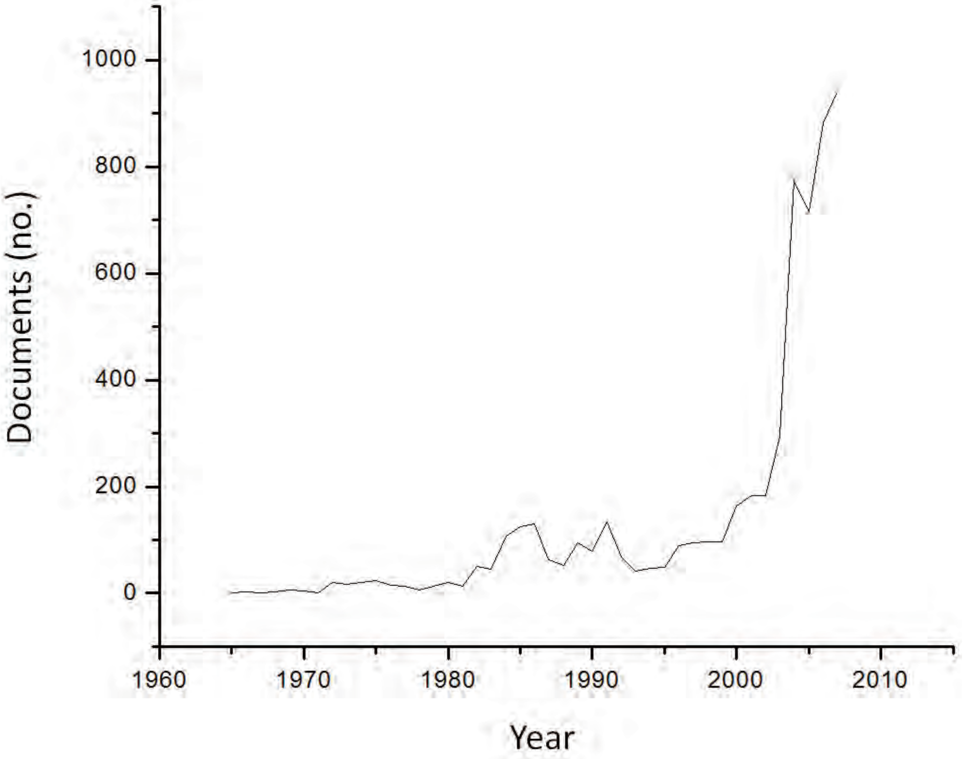

FIGURE B.1 Number of documents published, by year, 1965-2009, related to the keyword "Propulsion" in the Scopus database. The search is refined by the word "Aerospace."

The total publication output since 1965 (Figure B.2) is led by two Chinese universities, closely followed by the California Institute of Technology's Jet Propulsion Laboratory (JPL), which after a drop in overall numbers is followed by NASA. Figure B.2 is likewise educational for showing which are the less prolific institutions. However, with respect to the top affiliations, it is perhaps more instructive to look at the breakdown in publication affiliations as a function of the past three decades, as seen below.

The period from 1980 to 1989 was clearly dominated by authors with affiliations in the United States. The top 10 list (Figure B.3) is led by NASA and has only one foreign affiliation, in eighth place (Japan Aerospace Exploration Agency [JAXA]). The period from 1990 to 1999 (Figure B.4) continued to be dominated by authors with U.S. affiliations. The top 10 list was still led by NASA but had two foreign affiliations, in seventh (Japan, JAXA) and ninth places (Germany, Deutsches Zentrum fur Luft- und Raumfahrt).

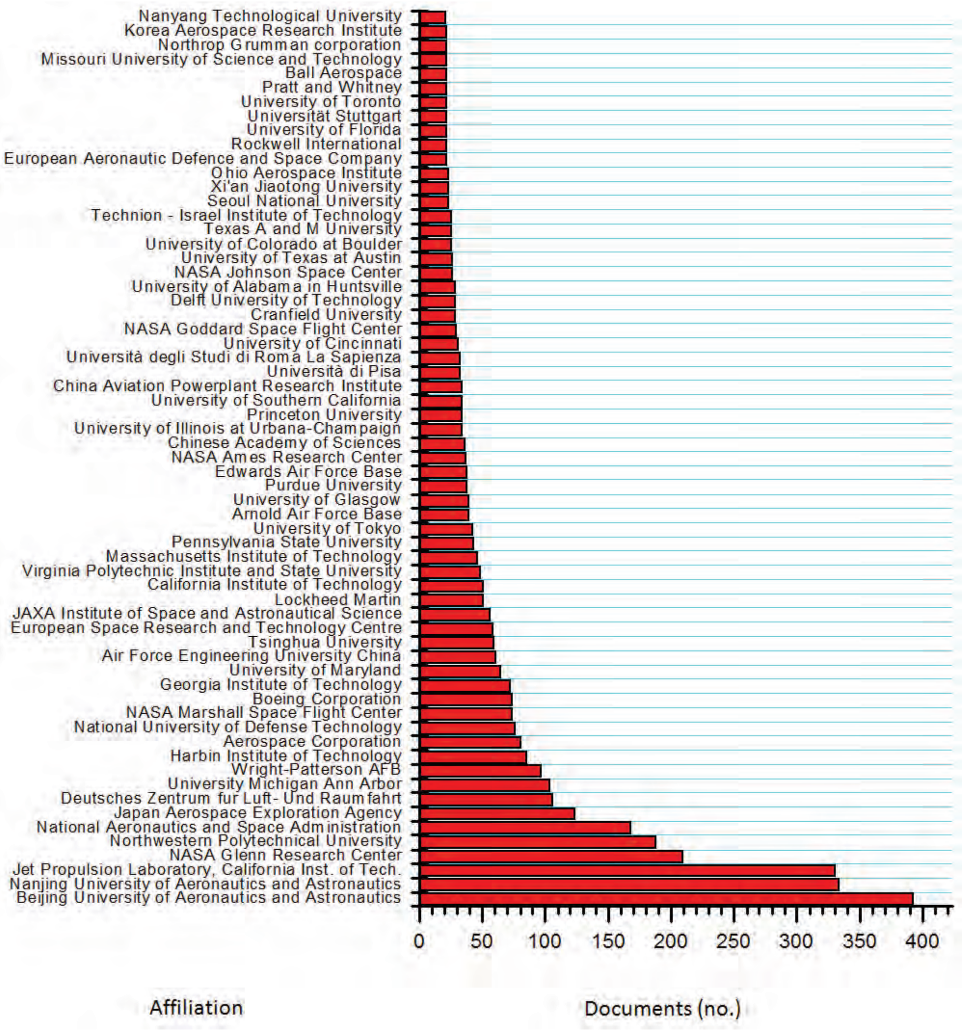

FIGURE B.2 Most common publication affiliations for documents related to the keyword "Propulsion" in the Scopus database for the years 1965-2009. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

The most recent period, from 2000 to 2009, is very different (Figure B.5). It is dominated by authors from two Chinese universities, in Beijing and Nanjing. The top 10 list shows the United States in third place; the affiliation is no longer NASA but JPL. Japan and Germany are still on the list, with China also in fifth and tenth place. Looking at overall publications, one can see in Figure B.6 that there is tremendous publication activity in the *Hangkong Dongli Xuebao Journal of Aerospace*

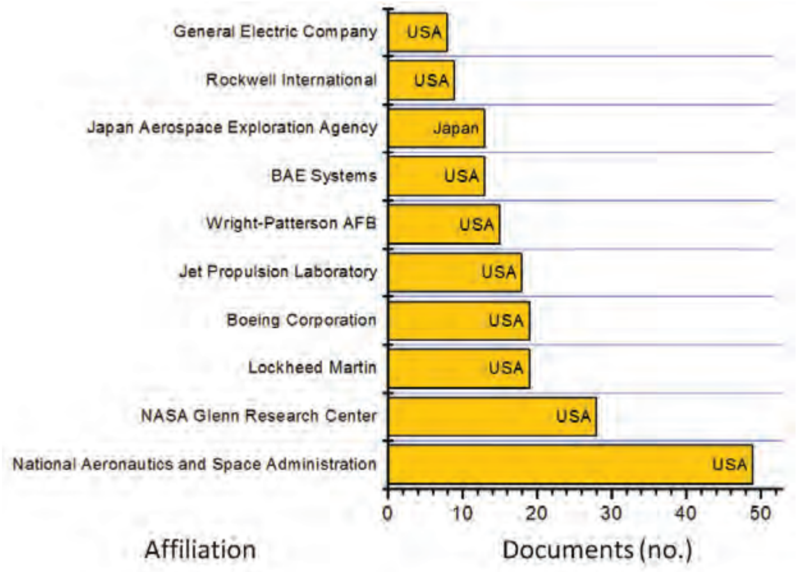

FIGURE B.3 Ten most common publication affiliations for documents related to the keyword "Propulsion" in the Scopus database for the decade 1980-1989. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

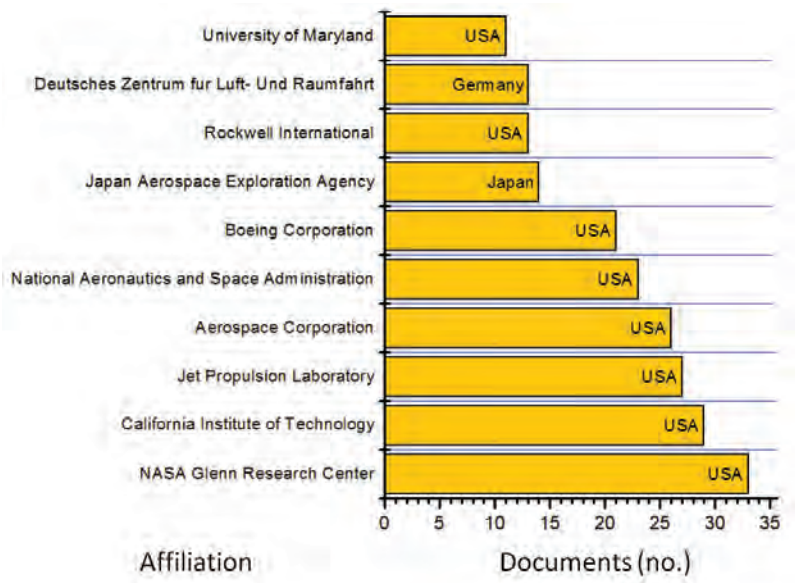

FIGURE B.4 Ten most common publication affiliations for documents related to the keyword "Propulsion" in the Scopus database for the decade 1990-1999. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

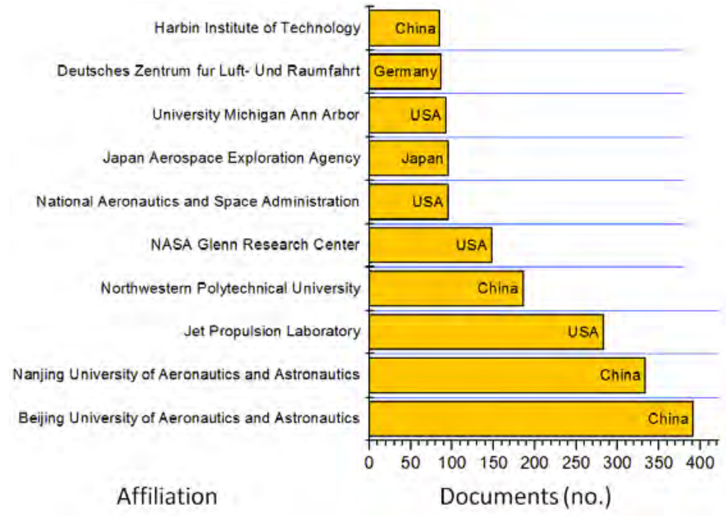

FIGURE B.5 Ten most common publication affiliations for documents related to the keyword "Propulsion" in the Scopus database for the decade 2000-2009. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

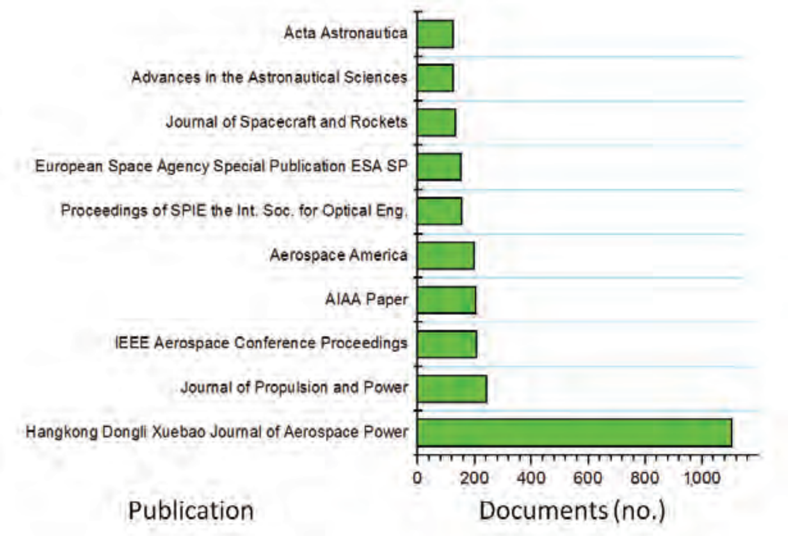

FIGURE B.6 Most common publications for documents related to the keyword "Propulsion" in the Scopus database for the years 1965-2009. The search is refined by the word "Aerospace." Publications are listed exactly as they appear in the Scopus database search results.

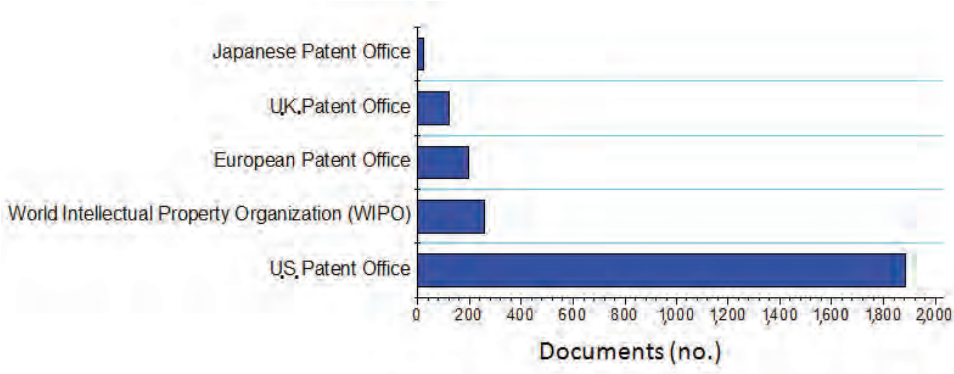

FIGURE B.7 Number of patents filed related to the keyword "Propulsion," as a function of patent office, for the years 1965-2009, according to data from the Scopus database. The search is refined by the word "Aerospace."

Power. Most of the other top 10 publication venues are from the United States, although the *European Space Agency Special Publication* (ESASP) is included.

As shown in Figure B.7, most propulsion-related patents are still filed in the United States. It is unclear if other countries keep their work as trade secrets or file in the United States in order to "secure" their influence in the U.S. arena.

B.2.2 Publications and Patents Related to Keyword "Hypersonic"

The field of hypersonics also saw a dramatic increase in the number of publication in the early 2000s, as indicated in Figure B.8.

Following, from the data for Figure B.8, is a list of the top 10 most prolific authors overall (according to Scopus), and in parentheses the number of their published documents, for the years 1970-2005, as indicated by a search for the keyword "Hypersonic"; the search is refined by the word "Aerospace."

- Jagadeesh, G. (31) India (Indian Institute of Science)
- Reddy, K.P.J. (29) India (Indian Institute of Science)
- Boyd, I.D. (26) USA (University of Michigan)
- Candler, G.V. (25) USA (Pennsylvania State University)
- Lewis, M.J. (23) USA (University of Maryland)
- Shang, J.S. (21) USA (Wright State University)
- Schneider, S.P. (20) USA (Purdue University)
- Gulhan, A. (20) Germany (German Aerospace Center)
- Holden, M.S. (18) USA (Calspan-University of Buffalo, SUNY)
- Zhong, X. (17) USA (University of California at Los Angeles)

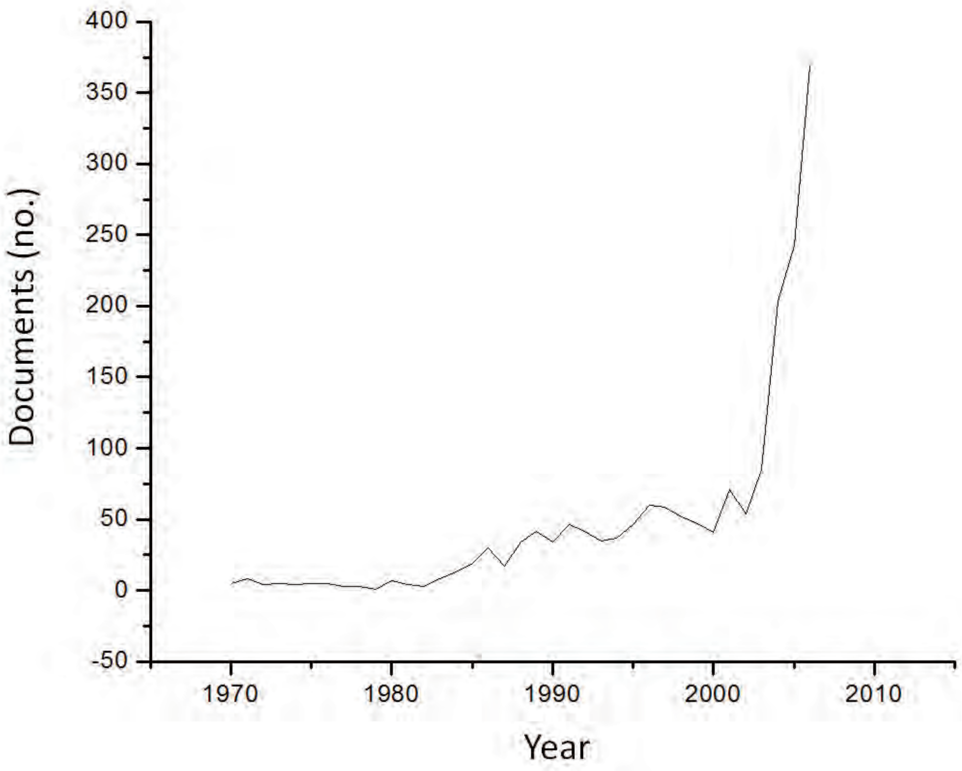

FIGURE B.8 Number of published documents, by year, 1970-2005, related to the keyword "Hypersonic" in the Scopus database. The search is refined by the word "Aerospace."

It is interesting to note that, according to the Scopus data for Figure B.8, various different authors contributed to the record of very active publishing seen for Japan and Germany, whereas a few highly prolific authors represented India and the United States, as indicated by the list above.

Clearly, published work in the hypersonics area for the 1968-2009 time period is dominated by NASA, followed by Japan, Germany, China, and India in some of the top spots (Figure B.9). The 2000-2009 period (Figure B.10) is also dominated by publications from NASA, followed by Nanjing University in China. This most recent decade also shows the presence of Japan, Germany, and India.

In the 1990-1999 decade (Figure B.11), there were more entries from both Japan and Germany (two each), and representation from France as well. In the 1980-1989 period (Figure B.12), however, NASA and the United States were enormously dominant in the hypersonics field. Thus a clear trend can be seen over

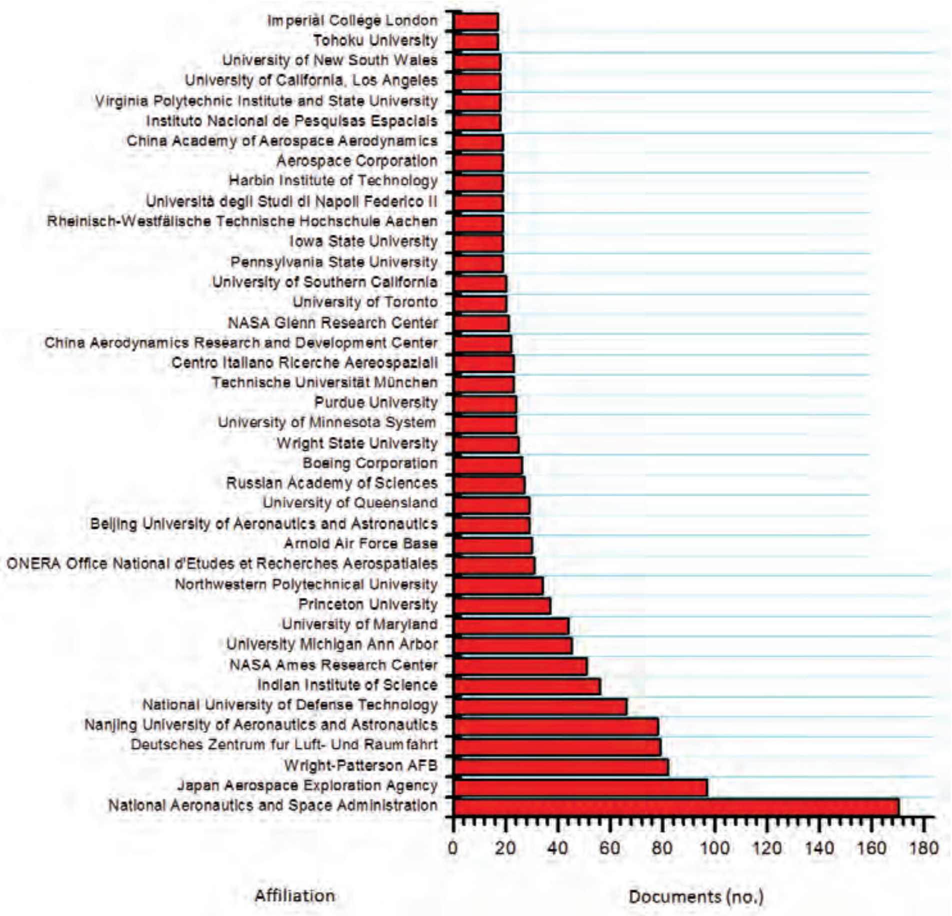

FIGURE B.9 Most common publication affiliations for documents related to the keyword "Hypersonic" in the Scopus database for the years 1968-2009 (that is, all years available in the database). The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

time: even though the output from NASA has increased, its lead over other prolific affiliations has declined dramatically.

As shown by the publication venues for hypersonics for 1968-2009 (Figure B.13) as cataloged in the Scopus database, the American Institute of Aeronautics and Astronautics is dominant through all its journals and papers, and AIAA's *Journal of Spacecraft and Rockets* is singled out as clearly in the lead. A non-U.S. publication—ESASP (Europe)—is only in position 10.

Again, as was the case with propulsion-related patents, the dominant patent office for hypersonic-related patents is the U.S. patent office (Figure B.14).

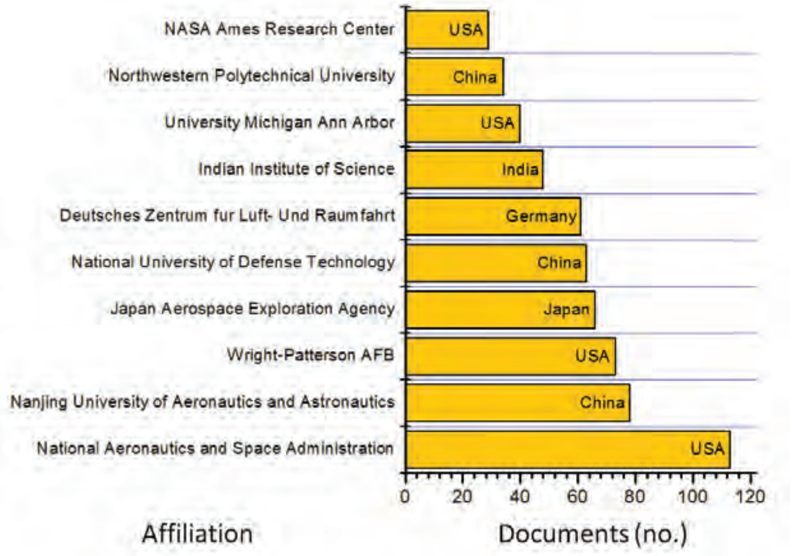

FIGURE B.10 Ten most common publication affiliations for documents related to the keyword "Hypersonic" in the Scopus database for the decade 2000-2009. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

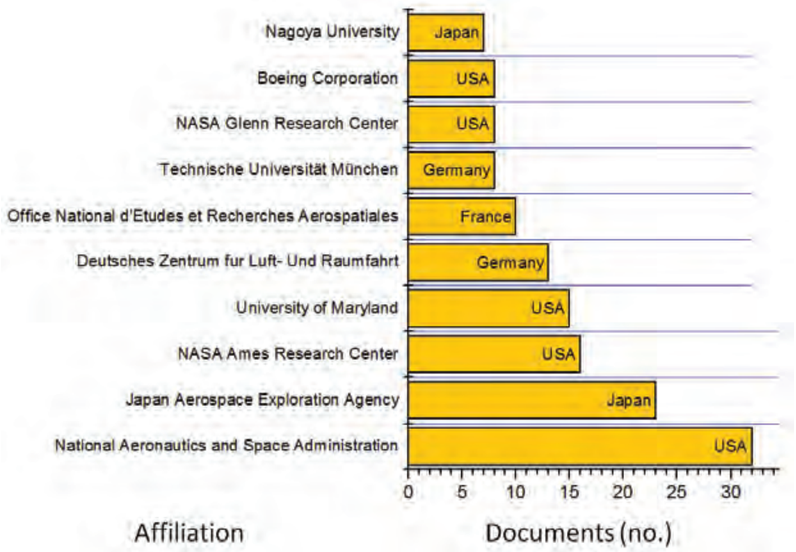

FIGURE B.11 Ten most common publication affiliations for documents related to the keyword "Hypersonic" in the Scopus database for the decade 1990-1999. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

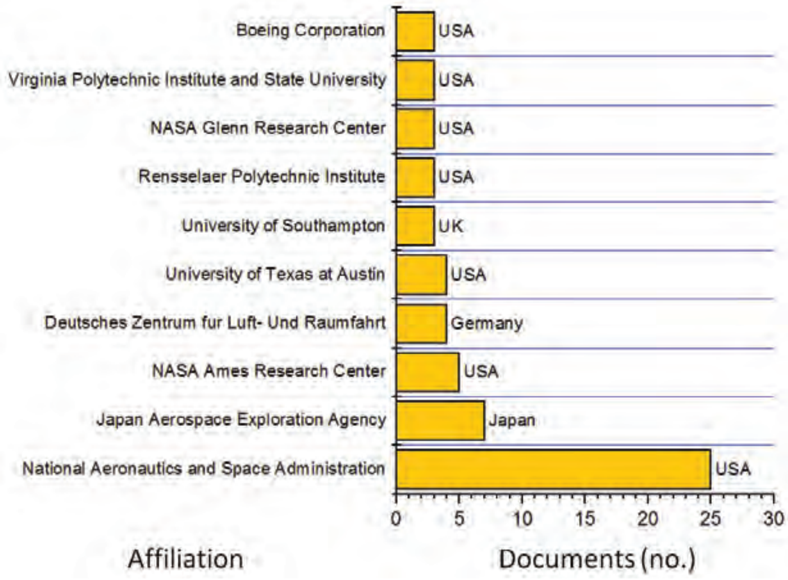

FIGURE B.12 Ten most common publication affiliations for documents related to the keyword "Hypersonic" in the Scopus database for the decade 1980-1989. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

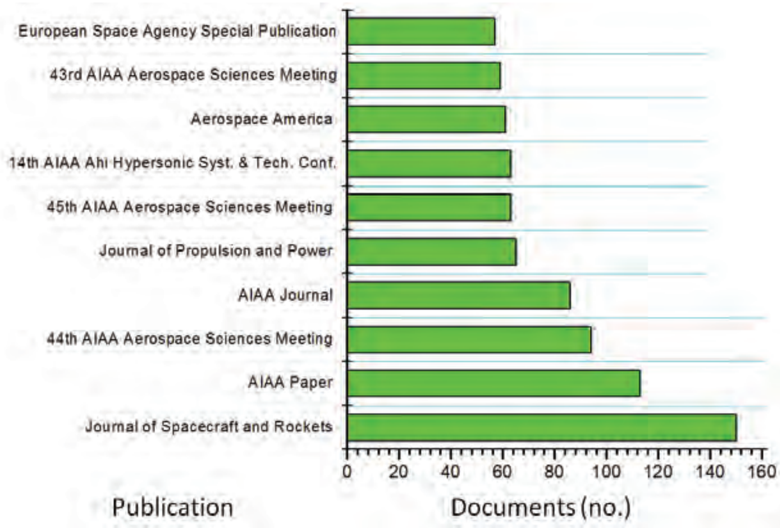

FIGURE B.13 Most common publications for documents related to the keyword "Hypersonic" in the Scopus database for the years 1968-2009. The search is refined by the word "Aerospace." Publications are listed exactly as they appear in the Scopus database search results.

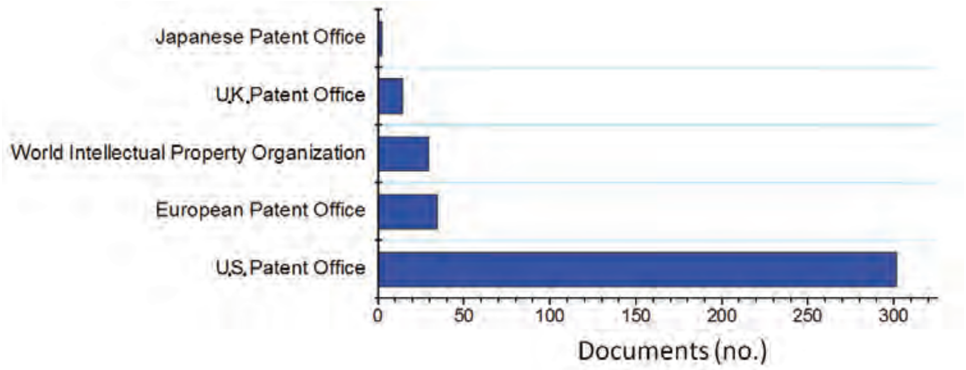

FIGURE B.14 Number of patents filed related to the keyword "Hypersonic," as a function of patent office, for the years 1968-2009, according to data from the Scopus database. The search is refined by the word "Aerospace."

B.2.3 Publications and Patents Related to Keyword "Scramjet"

"Scramjet," like "hypersonic" and "propulsion," has been the topic of an increasing number of documents published since the early 2000s (Figure B.15).

Looking at the affiliation for published documents over the 1970-2005 time period (Figure B.16), it is seen that NASA leads the field, closely followed by Japan, and followed in fourth position by China and Australia.

Looking at the top data by decades gives another picture for the most recent decade, 2000-2009 (Figure B.17). Here Japan is in the lead, with affiliations in China holding half of the top 10 positions. Previously (1990-1999) there had been a more distinct lead, by the United States and Japan, and no affiliations related to China (Figure B.18).

For the earliest period analyzed (1980-1989), the lead was clearly related to NASA publications, with Australia as the only other country on the top 10 list (Figure B.19). In conclusion, for the scramjet field it is clear that the domination of U.S. contributions to the body of published knowledge is rapidly diminishing, even though its contributions have increased in absolute numbers.

The publication venues for the 1970-2009 period are dominated by the *Journal of Propulsion and Power*. The other top 10 spots include several AIAA venues but also two Chinese journals (Figure B.20).

Following is a list of the top 10 most prolific authors overall, and in parentheses the number of their published documents for the years 1970-2009 (according to Scopus), as indicated by a search for the keyword "Scramjet." It is clear from this list that some of the Japanese authors have been very prolific in publishing results in comparison with results for U.S. authors.

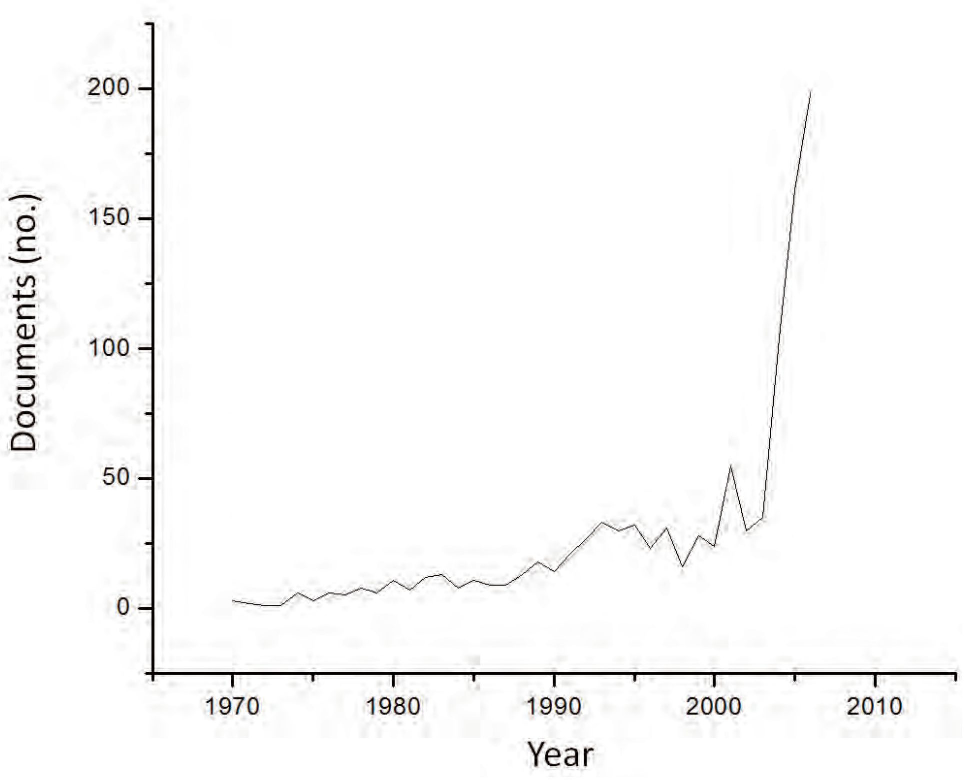

FIGURE B.15 Number of published documents each year, 1970-2005, related to the keyword "Scramjet" in the Scopus database.

- Kanda, T. (33) Japan (Kakuda Space Center)
- Wang, Z.G. (25) China (National University of Defense Technology)
- Mitani, T. (23) Japan (Japan Aerospace Exploration Agency)
- Tani, K. (22) Japan (Kakuda Space Center)
- Tomioka, S. (22) Japan (Kakuda Space Center)
- Zhang, K.Y. (21) China (Nanjing University)
- Schetz, J.A. (21) USA (Virginia Polytechnic Institute)
- Paull, A. (21) Australia (University of Queensland)
- Masuya, G. (20) Japan (Tohoku University)
- Murakami, A. (18) Japan (Kakuda Space Center)

Figure B.21 lists the number of patents related to the keyword "Scramjet" filed at five patent offices for the years 1970-2009.

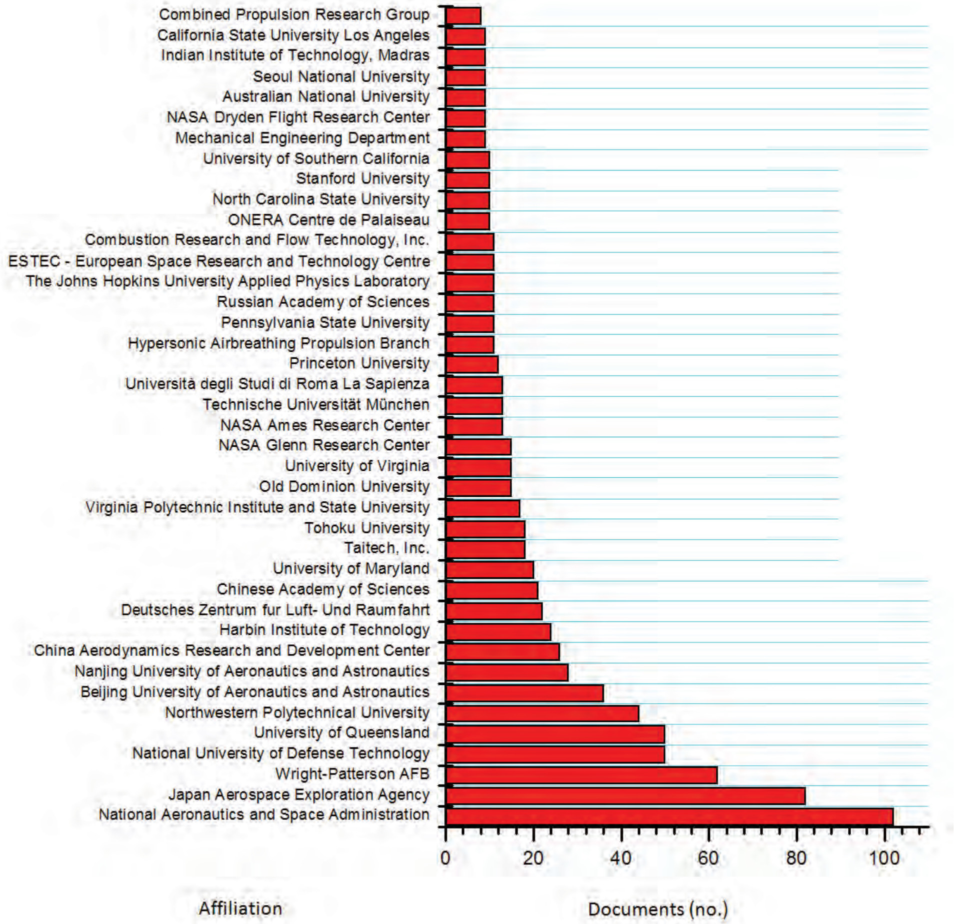

FIGURE B.16 Most common publication affiliations for documents related to the keyword "Scramjet" in the Scopus database for the years 1970-2009. Affiliations are listed exactly as they appear in the Scopus database search results.

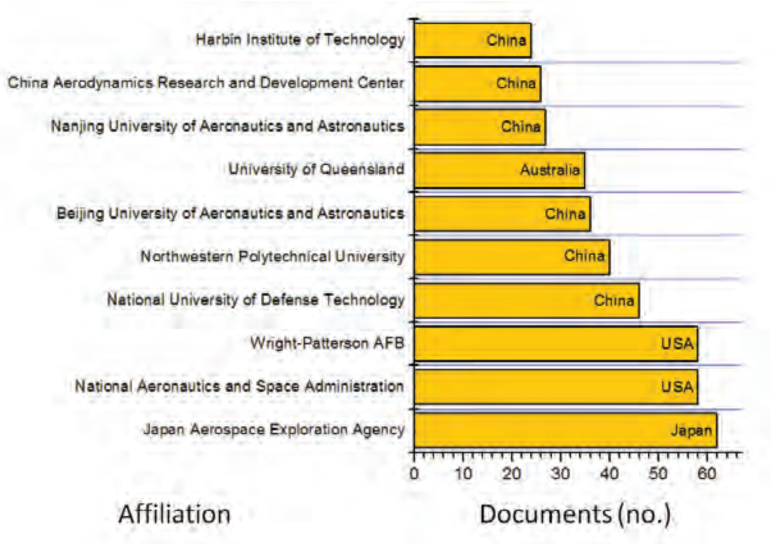

FIGURE B.17 Ten most common publication affiliations for documents related to the keyword "Scramjet" in the Scopus database for the decade 2000-2009. Affiliations are listed exactly as they appear from the Scopus database search results.

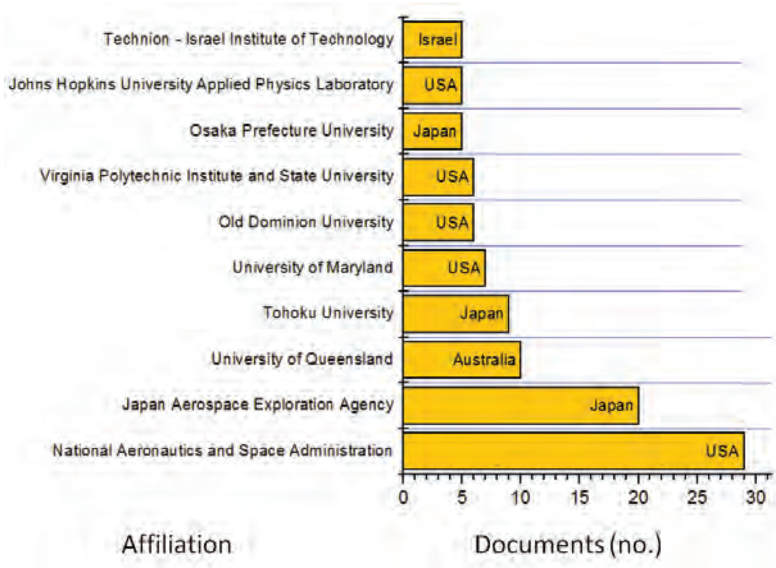

FIGURE B.18 Ten most common publication affiliations for documents related to the keyword "Scramjet" in the Scopus database for the decade 1990-1999. Affiliations are listed exactly as they appear in the Scopus database search results.

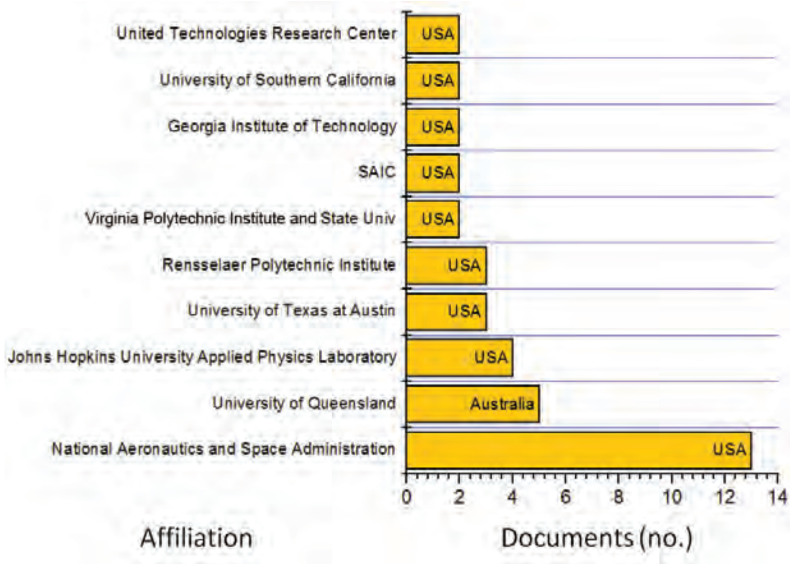

FIGURE B.19 Ten most common publication affiliations for documents related to the keyword "Scramjet" in the Scopus database for the decade 1980-1989. Affiliations are listed exactly as they appear in the Scopus database search results.

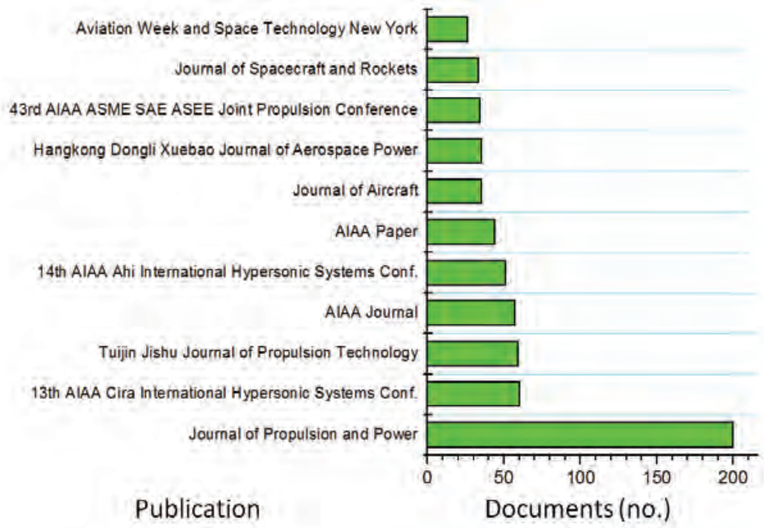

FIGURE B.20 Most common publications for documents related to the keyword "Scramjet" in the Scopus database for the years 1970-2009. The search is refined by the word "Aerospace." Publications are listed exactly as they appear from the Scopus database search results.

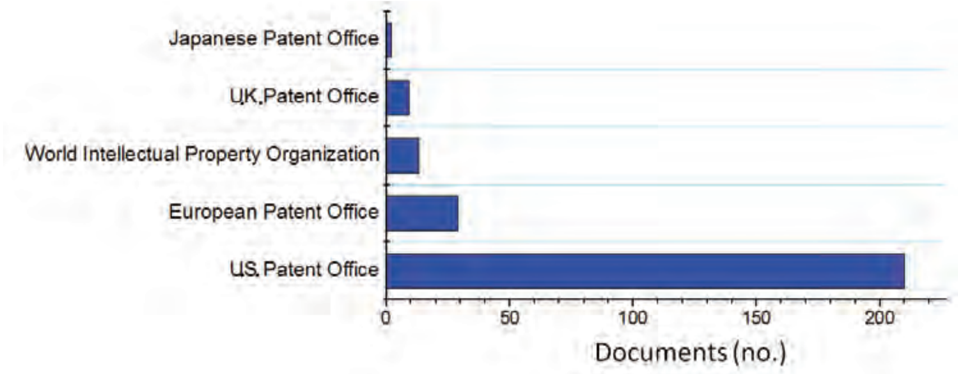

FIGURE B.21 Number of patents filed related to the keyword "Scramjet," as a function of patent office, for the years 1970-2009, according to data from the Scopus database.

B.2.4 Publications and Patents Related to Keyword "Supersonic"

The field of supersonics has had the same upswing in publications as that experienced in all the other areas described here, albeit with some notable smaller peaks all the way back to 1985 (Figure B.22).

Following is a list of the top 10 most prolific authors overall, and in parentheses the number of their published documents, for the years 1970-2005 (according to Scopus), as indicated by a search for the keyword "Supersonic"; the search is refined by the word "Aerospace."

- Schetz, J.A. (29) USA (Virginia Polytechnic Institute)
- Wang, Z.G. (28) China (National University of Defense Technology)
- Nakahashi, K. (24) Japan (Tohoku University)
- Setoguchi, T. (23) Japan (Saga University)
- Tomioka, S. (22) Japan (Japan Aerospace Exploration Agency)
- Rathakrishnan, E. (22) India (Indian Institute of Technology, Kanpur)
- Dutton, J.C. (21) USA (University of Illinois at Urbana-Champaign)
- Bobashev, S.V. (21) Russia (Russian Academy of Sciences)
- Miles, R.B. (20) USA (Princeton University)
- Zhou, J. (19) China (National University of Defense Technology)

The most prolific affiliations of published material in the supersonics area are clearly the Japanese Aerospace Exploration Agency and, in second place, NASA. These are followed by China, Germany, and Russia in the nearest top positions (Figure B.23). This ordering is also reflected in the subset of publications during the past 10 years (Figure B.24).

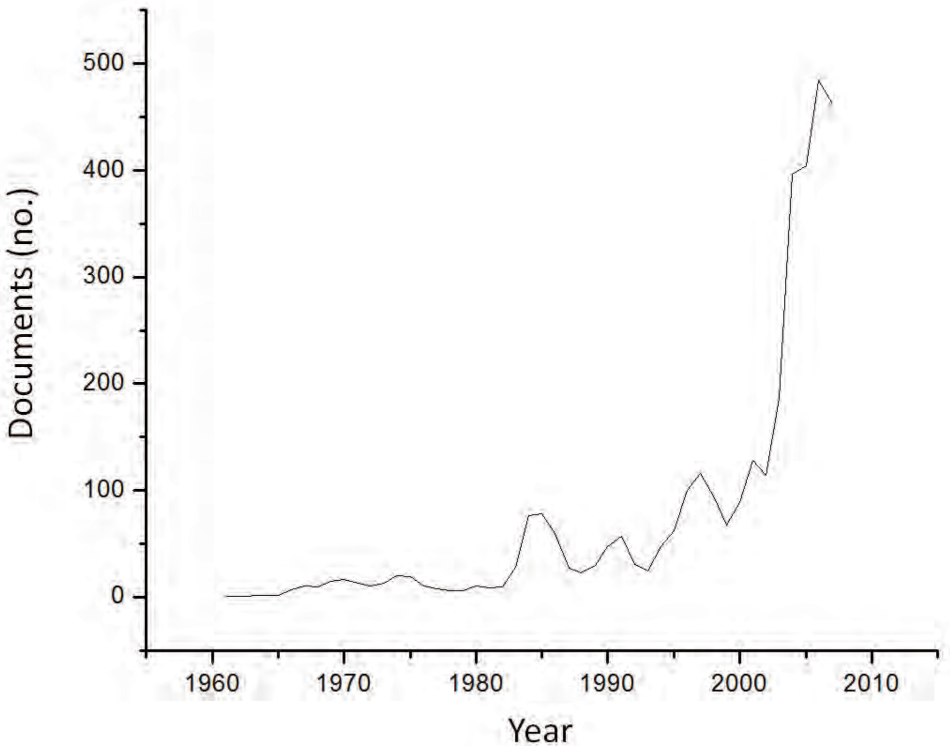

FIGURE B.22 Number of published documents, by year, 1970-2005, related to the keyword "Supersonic" in the Scopus database. The search is refined by the word "Aerospace."

Looking back to the decade 1990-1999, China and Russia were not publishing and/or doing as much work as in 2000-2009. Also, the Israel Institute of Technology, which was very active in this field in 1990-1999 (Figure B.25), is no longer among the countries with the most prolific affiliations.

Even farther back (1980-1989), except for the United States, only Canada and Japan were on the list, in the two last spots (Figure B.26). It is also noteworthy that there were more companies on the list during the decade 1980-1989 (today there are none among the top 10; see Figure B.24).

The publication sources in the top 10 list are clearly dominated by AIAA-related and U.S. venues (Figure B.27).

And finally, a look at the number of patents filed related to the keyword "Supersonic" for the years 1961-2009 (Figure B.28), with the search refined by the word "Aerospace," shows a trend similar to that seen with patent filings related to the other keywords.

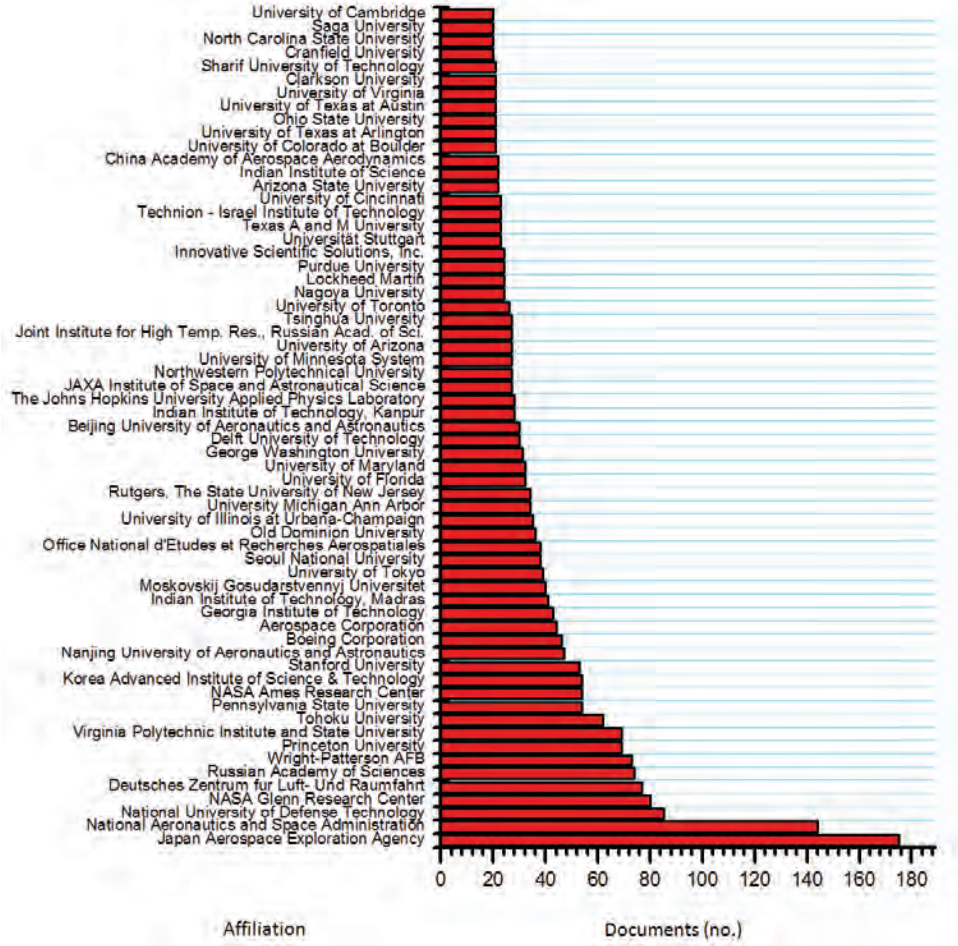

FIGURE B.23 Most common publication affiliations for documents related to the keyword "Supersonic" in the Scopus database for the years 1961-2009. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

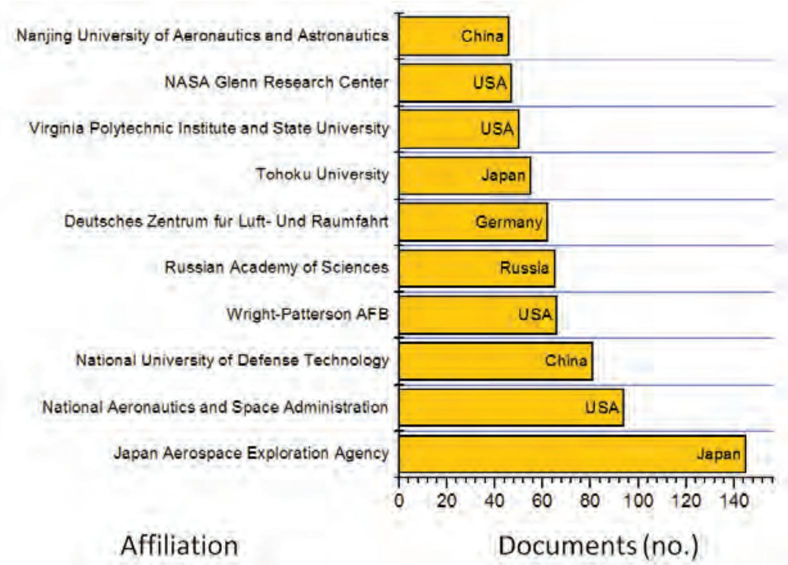

FIGURE B.24 Ten most common publication affiliations for documents related to the keyword "Supersonic" in the Scopus database for the decade 2000-2009. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

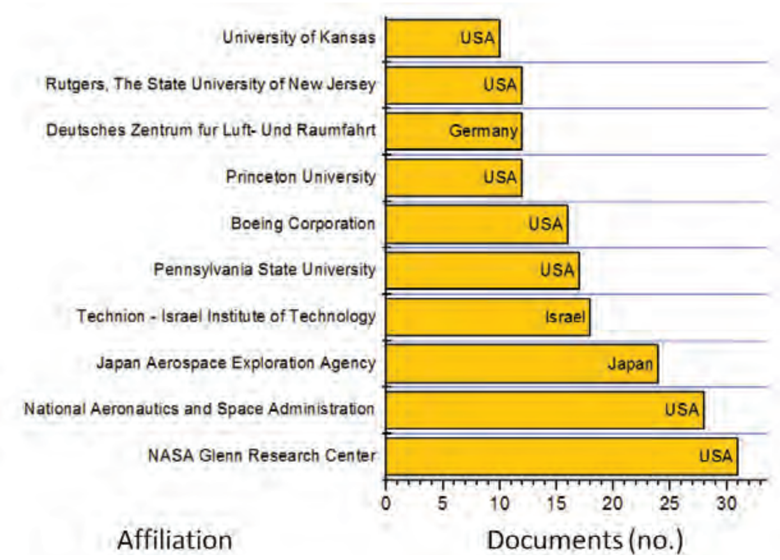

FIGURE B.25 Ten most common publication affiliations for documents related to the keyword "Supersonic" in the Scopus database for the decade 1990-1999. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

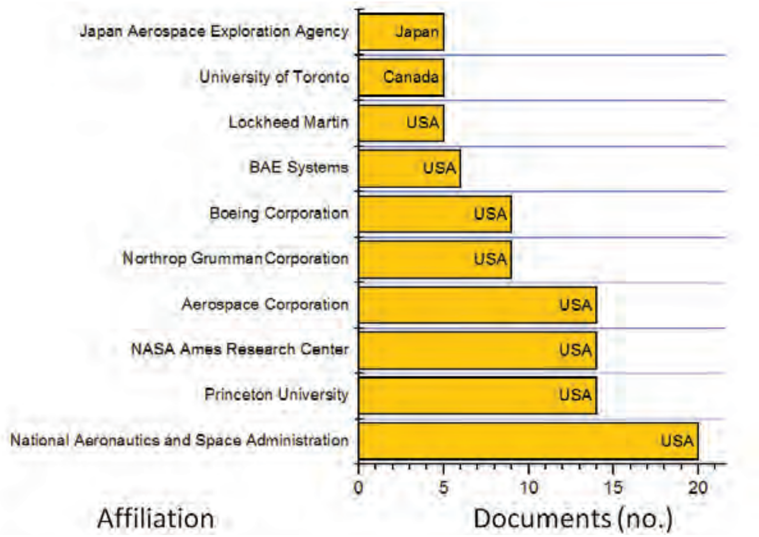

FIGURE B.26 Ten most common publication affiliations for documents related to the keyword "Supersonic" in the Scopus database for the decade 1980-1989. The search is refined by the word "Aerospace." Affiliations are listed exactly as they appear in the Scopus database search results.

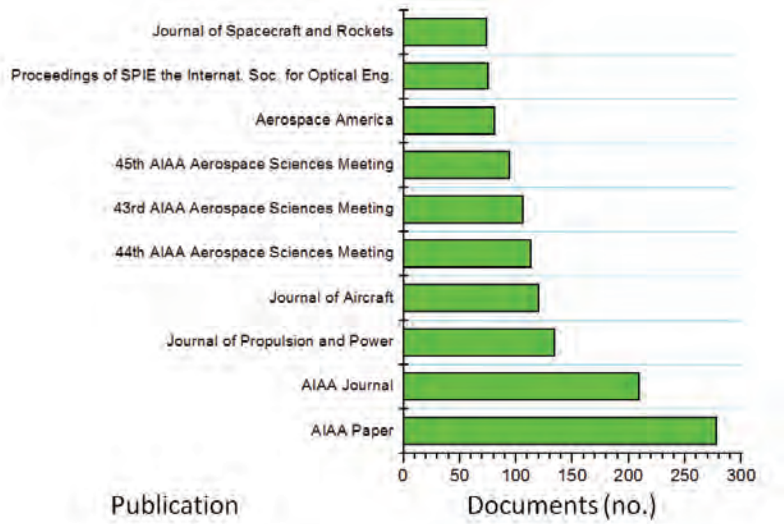

FIGURE B.27 Most common publications for documents related to the keyword "Supersonic" in the Scopus database for the years 1961-2009. The search is refined by the word "Aerospace." Publications are listed exactly as they appear in the Scopus database search results.

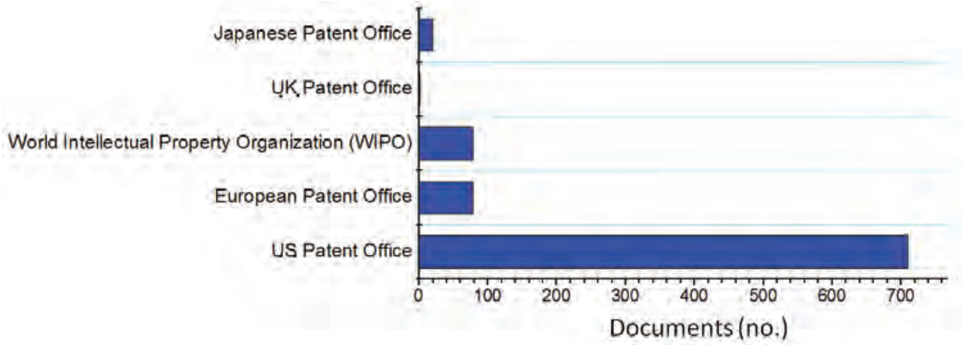

FIGURE B.28 Number of patents related to the keyword "Supersonic" filed at five patent offices, for the years 1961-2009, according to data from the Scopus database. The search is refined by the word "Aerospace."

C

Biographies of Committee Members

George K. Muellner, *Chair,* is the retired president, Advanced Systems for Integrated Defense Systems of the Boeing Company. He was responsible for all advanced development programs before the initiation of production. Prior to holding that position he was responsible for all programs that the company conducted for the U.S. Air Force or international air force customers. Prior to this assignment, Mr. Muellner was the president of Phantom Works, Boeing's advanced research and development unit, dedicated to improving the quality, performance, and affordability of Boeing products and services through technology development, process improvement, and new product development. He also served as a lieutenant general in the U.S. Air Force. He was the principal deputy to the Assistant Secretary of the Air Force for Acquisition. He provided direction, guidance and formulation, review, and approval and execution of plans, policies, and programs relative to acquisition. He was also designated as the Air Force chief information officer. He had previously served as the initial program executive officer for the Joint Advanced Strike Technology Program (now designated the Joint Strike Fighter Program). He is a fellow of the Society of Experimental Test Pilots and of the Royal Aeronautical Society and a past president and fellow of the American Institute of Aeronautics and Astronautics.

Daniel G. Backman joined the Mechanical Engineering Department of Worcester Polytechnic Institute as a research professor following a 26-year career with GE Aircraft Engines. Dr. Backman received his SB, SM, and ScD degrees from the Massachusetts Institute of Technology. He went on to hold an assistant professorship at the University of Illinois at Urbana-Champaign and then joined GE, where he provided materials application engineering support and carried out research on aerospace materials and processes. More recently, he contributed to the development of the disk alloy for the NASA High Speed Civil Transport and led the Defense Advanced Research Projects Agency (DARPA)-sponsored Accelerated Insertion of Materials initiative at GE. Much of Dr. Backman's work has focused on mathematical modeling of material processes and the development and implementation of intelligent processing of materials methods for aircraft engine materials. At the time of his retirement from GE, Dr. Backman was the organizational leader of the Materials Modeling and Simulation section. He has served on a number of national technical committees and a corporate board and has three patents on aerospace materials. Dr. Backman served as a member of the National Research Council's Committee on Integrated Computational Materials Engineering.

Charles E. Browning is the Torley Chair in Composite Materials at the Chemical and Materials Engineering Department at the University of Dayton. He received his BS in chemistry from West Virginia University, his MS in chemistry from Wright State University, and his PhD in materials engineering from the University of Dayton. Before joining the faculty at the University of Dayton, he had been the director of the Materials and Manufacturing Directorate of the Air Force Research Laboratory. Dr. Browning was responsible for the planning and execution of the Air Force's advanced materials, processes, and manufacturing and environmental technology programs to support all elements of Air Force acquisition and sustainment. He was also responsible for interfacing these specific areas throughout the corporate Air Force and Department of Defense. At the Materials and Manufacturing Directorate he headed an organization of approximately 530 government employees, with a yearly budget of nearly $400 million. Dr. Browning began his career with the Air Force in 1966 and has held various senior technical and management positions within the laboratories. He was appointed to the Senior Executive Service in 1998. He has received numerous awards, including the Outstanding Engineer and Scientist Award from the Affiliates Society Council of Dayton, the Materials Laboratory Cleary Award for Scientific Advancement, the Materials Laboratory Schwartz Award for Engineering Excellence, the Materials Directorate Management Excellence Award, and the 2002 Meritorious Executive Presidential Rank Award. He is a member of the American Chemical Society and the Society for the Advancement of Material and Process Engineering.

William G. Fahrenholtz is a professor of ceramic engineering in the Department of Materials Science and Engineering at the Missouri University of Science and Technology (formerly the University of Missouri-Rolla). He earned BS and MS degrees in ceramic engineering at the University of Illinois at Urbana-Champaign in 1987 and 1989, respectively. He completed his PhD in chemical engineering at the University of New Mexico (UNM) in 1992. From 1993 to 1999, Dr. Fahrenholtz was a research assistant professor in the Department of Chemical and Nuclear Engineering at UNM. In 1999, he took a job as an assistant professor at the Missouri University of Science and Technology. He was promoted to associate professor with tenure in 2005 and to full professor in 2008. He has received several awards, including six campus-wide faculty excellence awards, two teaching awards, and a prestigious CAREER award from the National Science Foundation. He was elected a fellow of the American Ceramic Society in 2007. Dr. Fahrenholtz teaches undergraduate and graduate courses on thermodynamics as well as a laboratory class on ceramic processing. His research focuses on the processing and characterization of ceramics and ceramic-metal composites. He has current projects related to ultrahigh-temperature ceramics as well as the use of cerium oxide coatings for the corrosion protection of high strength aluminum alloys. He has published more than 60 papers in peer-reviewed journals and given more than 20 invited presentations on his research.

Wesley L. Harris is the Charles Stark Draper Professor and head of the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology. His research focuses on theoretical and experimental unsteady aerodynamics and aeroacoustics, computational fluid dynamics, and the government policy impact on procurement of high-technology systems. Prior to this position, he served as the associate administrator for aeronautics at NASA. He has also served as the vice president and chief administrative officer of the University of Tennessee Space Institute. Dr. Harris has served on committees of the American Institute of Aeronautics and Astronautics (AIAA), the American Helicopter Society (AHS), and the National Technical Association, and as adviser to eight colleges, universities, and institutes. Dr. Harris earned a BS in aerospace engineering from the University of Virginia and an MS and a PhD in aerospace and mechanical sciences from Princeton University. He was elected a fellow of the AIAA and of the AHS for personal engineering achievements, engineering education, management, and advancing cultural diversity. Dr. Harris has served as chair and member of various boards and committees of the National Research Council (NRC), the National Science Foundation, the U.S. Army Science Board, and several state governments. He is a current member of the NRC's Division on Engineering and Physical Sciences Committee, the National Academy of Engineering's Grand Challenges for Engineering Committee, and the Committee on Engineering Education, and he served as chair of the Committee on Assessing Corrosion Education.

S. Michael Hudson was vice chair, Rolls-Royce North America Holdings, before his retirement. He led an investment group in the purchase of Detroit Edison's distributed generation business in Anderson, Indiana, in 2005 and serves as chair of I Power, the company formed from that acquisition. He also held the position of president, chief executive officer of Rolls-Royce Allison following its acquisition by Rolls-Royce in 1995. He served as chief operating officer and chief financial officer at various times during this period. Following his graduation from the University of Texas with a BS degree in mechanical engineering, Mr. Hudson was employed by Pratt and Whitney Aircraft from 1962 to 1968. He was one of two managers who, with Clayton Dubilier, acquired Allison Gas Turbine from General Motors Corporation. He has served on the management boards of several joint-venture companies in which Rolls-Royce Allison has had interest.

He is a member of the board of directors of the Indianapolis Water Company. He is a fellow of the Society of Automotive Engineers and the Royal Aeronautical Society, an honorary fellow of the American Helicopter Society (AHS), and an associate fellow of the American Institute of Aeronautics and Astronautics (AIAA). In professional society work, Mr. Hudson has been a member of the AIAA Propulsion Committee and the AHS Propulsion Committee and has been chair of the AHS board of directors. Mr. Hudson has been a member of the board of directors of the National Association of Manufacturers and of the Society of Automotive Engineers (SAE) and has served as chair of the SAE's Aerospace Council and been on its Aerospace Program Office Committee and its Finance Committee. He has received the SAE Franklin W. Kolk Air Transportation Progress Award and the Royal Aeronautical Society British Gold Medal and has been associated with five Collier Trophy-winning programs. He has served on the Aerospace Industries Association Technical Council and chaired its Civil Aviation Division. Mr. Hudson's publications range from technical work on propulsion to defense procurement and business initiatives. He has served on Air Force and Department of Defense review groups, including ad hoc committees to the Science Advisory Board, the Defense Science Board Task Force on Commercial Procurement, and the Industry Review Group of the Integrated High Performance Turbine Engine Technology Initiative.

For NASA, Mr. Hudson was a member of the Aeronautics Advisory Committee and the Subcommittee on Rotorcraft Technology, and he chaired the Propulsion Aeronautics Research and Technology Subcommittee. He also served on the National Research Council Committee on Strategic Assessment of the U.S. Aeronautics Program, the Committee on Aeronautics Research and Technology for Environmental Compatibility, the Committee on Engine Efficiency for USAF Non-fighter Aircraft, the Committee on Aeronautics Research and Technology for Vision 2050, and the Committee on NASA's Revolutionize Aviation Strategic Plan, and he has been a member of the National Research Council's Aeronautics and Space Engineering Board. Mr. Hudson is on various local university and civic boards and has chaired or been a member of charitable fund-raising activities. He has served as a visiting professor at Cranfield University in the United Kingdom and is a member of the board of trustees of Marian College, the Purdue University Discovery Park Advisory Board, and the Richard G. Lugar Center for Renewable Energy Advisory Board.

Sylvia M. Johnson serves as the chief materials technologist, Entry Systems and Technology Division, at the NASA Ames Research Center. From 2000 to 2009, she was chief of the Thermal Protection Materials and System Branch of the NASA Ames Research Center. Prior to that, Dr. Johnson was the director of Ceramic and Chemical Product Development at SRI International. She joined SRI after receiving her PhD in materials science from the University of California, Berkeley, in 1983. Dr. Johnson's research efforts have involved the synthesis of oxide and non-oxide ceramic powders; the processing, characterization, and evaluation of structural ceramics, especially silicon nitride; and methods for joining ceramics. Most recently, she has worked on ultrahigh-temperature ceramics and on ablative materials and coatings, both for thermal protection systems. A fellow of the American Ceramic Society since 1992, Dr. Johnson served as its vice president in 1996-1997 and as an elected board member from 2002 to 2005. In addition to holding many committee assignments, she has been counselor of the Northern California section since 1988 and has chaired five Pacific Coast Regional Meetings. She was chair of PACRIM5, an international conference held in 2005. She is currently the American Ceramic Society representative to the International Ceramic Federation. From 1997 to 2002, Dr. Johnson served on the National Materials Advisory Board (NMAB). During that time, she chaired two NMAB materials forums, was chair of the NMAB Workshop on Education and the Workforce in Materials Science and Engineering, and participated in a number of materials studies. She most recently served on the Committee on Assessing Corrosion Education (ACE). She has served on the National Institute of Standards and Technology Materials Evaluation Board and on the organizing committee of the National Space and Missile Materials Symposium, and she currently serves on the Evaluation Board for Materials Science and Technology at the Sandia National Laboratories and the Advisory Board for Ceramic Engineering at Missouri University of Science and Technology. She is a National Associate of the National Research Council. Dr. Johnson has published approximately 50 papers, edited 2 books, and received 5 U.S. patents.

William L. Johnson is the Ruben and Donna Mettler Professor of Materials Science at the California Institute of Technology (Caltech), having joined the Caltech faculty in 1977. He received his BA in physics from Hamilton College and his PhD in applied physics from Caltech. He spent 2 years at IBM's Thomas J. Watson Research Center (1975-1977) prior to joining the faculty at Caltech. Dr. Johnson's research interests are centered on non-equilibrium thermodynamic systems. In the mid-1980s, he, along with Ricardo Schwarz, discovered solid-state amorphization, leading to many years of fruitful research. His research accomplishments include the first studies of superconductivity in metallic glasses, pioneering studies of crystal-to-glass transformations. This work was followed by the synthesis of nanocrystalline and amorphous materials by high-energy ball milling, and, in 1993, the discovery of bulk metallic glasses (BMG). Dr. Johnson pioneered the discovery, characterization, and science of BMG forming alloys and their use as engineering materials. His recent work has involved the development of a theory that establishes fundamental physical principles governing flow in amorphous materials. His research has led to commercial success—he is an inventor on more than 25 issued patents. He is a cofounder of Liquidmetal Technologies, in Lake Forrest, California, which commercialized one of Dr. Johnson's BMG alloys for golf club heads (under the company name "LiquidMetal Golf"). The company is now pursuing opportunities in cases for electronic devices. It is also expanding into the defense industry, as some of the BMG composites have demonstrated properties superior to depleted uranium as high-velocity penetrators. Dr. Johnson served on the editorial board of the *Journal of Rapid Solidification* and serves as an associate editor for the *Journal of Applied Physics* and *Applied Physics Letters*. He was a principal editor of the *MRS Journal of Material Science*. He is the author or co-author of more than 360 publications in the scientific literature and has contributed chapters to 7 books. He has held numerous consulting positions for the Department of Energy, NASA, and corporations. Over the past two decades, he has been a consultant and on numerous advisory panels for the U.S. Department of Energy, NASA, the National Science Foundation, and the National Academy of Engineering.

Eric J. Jumper is a professor in the Aerospace and Mechanical Engineering Department at the University of Notre Dame, where he is also a member of the Center for Flow Physics and Control and directs the Aero-Optics Laboratory in the University of Notre Dame's Hessert Laboratory for Aerospace Research. His research includes work on aero-optics, turbomachines and turbofans, and aircraft wake dynamics. He has also taught at both the United States Air Force Academy in Colorado Springs, Colorado, and at the Air Force Institute of Technology in Dayton, Ohio. In addition to his academic appointments, Dr. Jumper has worked as a research aerodynamicist and as chief of the Laser Devices Division at the Air Force Weapons Laboratory. He holds a BS from the University of New Mexico, an MS in mechanical engineering from the University of Wyoming, and a PhD in gas dynamics and laser physics from the Air Force Institute of Technology. His expertise is in military acquisition and procurement, aerospace engineering, space science, government technical program management, physics, thermodynamics, propulsion and combustion, orbital mechanics, aerodynamics, reentry heating and thermal protection materials, surface chemistry, and aero-optics.

Robert H. Latiff is recently retired as vice president, chief engineer and technology officer in Science Applications International Corporation's (SAIC) Space and Geospatial Intelligence Business Unit. He retired from the U.S. Air Force as a major general, with his last assignments at the National Reconnaissance Office as the director for systems engineering and as the director of advanced systems and technology. General Latiff was a career acquisition officer, managing large, complex systems such as the Cheyenne Mountain Complex, the Air Force's airspace management and landing systems, and the Joint Surveillance Target Attack Radar System (JSTARS). General Latiff holds MS and PhD degrees in materials science and a BS in physics from the University of Notre Dame.

Judith Schneider is an associate professor in the Mechanical Engineering Department of Mississippi State University. She obtained her MS and PhD degrees from the University of California, Davis, in 1993 and 1996, respectively. Following her graduation, she was employed as a postdoctoral researcher at the Sandia National Laboratories in Livermore, California, and at the Max Planck Institute for Powder Metallurgy in Stuttgart, Germany. Dr. Schneider's research thrust is correlation of the environmental effects, such as temperature and strain rate, on the mechanical performance of structural materials. Much of her research centers on the characterization of the microstructural evolution during either the processing or service life of the material. This area of research focuses on how materials can be fabricated to produce suitable microstructures for specific structural applications. Her approach is to design experiments that decouple the predicted events to quantify the deformation conditions and correlate this with the microstructural evolution and material behavior. To achieve this goal, experiments are designed to decouple the physical events to verify and validate the analytical treatment of the process. Prior to earning her graduate degrees in materials science, Dr. Schneider was employed as a design/testing engineer at Aerojet Propulsion Company in Sacramento, California. There she was involved in the design, fabrication, and testing of prototype liquid rocket engines.

D

ITAR-Restricted Analysis of the Plan

The text of this appendix contains information that is not releasable to the public under International Traffic in Arms Regulations. Requests for this material (reference case number 88ABW-2010-6410) shall be directed to the Office of Security of the National Academy of Sciences.

E

Materials Development Case Studies

The U.S. propulsion community has a long and successful history of bringing advanced materials to fruition as measured in terms of more capable military systems and commercial systems. It is instructive to examine several of the advanced materials through the development process to identify how the successful materials and manufacturing processes produced propulsion advances or in some cases did not realize the expected potential of the material.

E.1 SUCCESS STORY IN MATERIALS, GAMMA TITANIUM ALUMINIDES (GEnx™)

The history of GE's efforts to utilize gamma titanium aluminides (TiAl) is an excellent case study of how the development process evolves.[1] In this case, the advanced material went through the traditional materials development process, but found application in a commercial engine rather than in the originally targeted military systems.

Realizing the benefits of gamma TiAl has been the goal of the aerospace industry for more than three decades. The promise of a materials system with half the density of nickel alloys and acceptable strength above 800°C is considerable, in particular for rotating airfoils. However, gamma TiAl alloys are a major departure from conventional Ti, Al, or Ni alloys and consequently required a significant level of

[1] Clay Haubert, GE Aviation, "GE Aviation Summary—Gamma TiAl for GEnx Low Pressure Turbine Blades," presentation and paper provided to the committee, January 30, 2009.

learning, process and facility development, and engineering application precursor work before they could be introduced into products. A clear lesson learned in this regard is the need to transition materials development from "technology push" to "technology pull" as quickly as possible so that all the requirements of the end application are identified early.

The amount of effort required for a new material introduction, especially for a new class of materials like TiAl, is beyond the level that any industrial company alone can support over the lengthy development process. Collaborative industry-government efforts were key to sustaining the needed "constancy of purpose" required to introduce new materials and processes into applications.

E.1.1 Timeline Outlining the History of Gamma TiAl Introduction at GE Aviation

1970s Through Early 1980s

In the period of the 1970s through the early 1980s, little direct GE work was done; there was considerable Air Force funding of work at government laboratories, universities, and Pratt and Whitney, including work to produce and rig test low-pressure turbine (LPT) blades and other engine components.

Mid- to Late 1980s

In the mid- to late 1980s, gamma TiAl research and development (R&D) continued work at Pratt and Whitney, government laboratories, and universities. Alloy development work was funded both internally and by the Air Force at GE's Global Research Center (GE GRC). GE alloy 48Al-2Cr-2Nb resulted from a chemistry matrix that was part of the internally funded work.

With respect to the criticality of the government-funded work, it is unlikely that GE would have pursued gamma TiAl without the precursor efforts or the parallel funding for alloy development work at GE GRC.

The end result of the 1980s' alloy work was the establishment of GE 48-2-2, a material that has a nominal room temperature elongation of approximately 2 percent and environmental resistance so that it does not require coatings for applications up to approximately 800°C. These are significant characteristics, as they make GE 48-2-2 attractive from an engineering and manufacturing standpoint. For comparison purposes, competing gamma TiAl alloys typically had nominal ductilities that were less than 1 percent and required environmental barrier coatings for extended use in the operational environment.

Approximately 1988

In about 1988, GE recognized the potential of GE 48-2-2 as a viable engineering material and began significant work on application-specific development, including casting, forging, and powder processing of GE 48-2-2. The funding of this work was entirely GE Aviation industry research and development (IR&D). Cast gamma TiAl work on GE 48-2-2 began in 1989. Fundamental producibility and cost assessments of the alternate approaches convinced GE that casting was the preferred method of manufacture for gamma TiAl engine parts.

1990-1994

During the 1990-1994 period, baseline GE90 weight requirements inspired a detailed assessment of the potential of TiAl applications. A review of GE-generated and historical government contract (Pratt and Whitney) reports convinced GE to pursue LPT blades. GE generated the first draft of the LPT blade design practice for a TiAl blade, including attachment considerations and key materials property requirements. An initial draft of a materials specification was also done.

To facilitate progress toward implementation of LPT blades, GE committed to designing, producing, and engine testing CF6-80C stage 5 LPT blades from GE 48-2-2. Howmet (Whitehall) cast the blades overstock. The blades were subsequently electrochemically milled to final shape. Since GE was not able to optimize the design for the TiAl material (the parts had to fit into the existing stage 5 space), damper pins were employed to avoid resonant frequencies during engine testing.

The ability (or lack of ability) by melters to control aluminum content within the range of the narrow specification (32 to 33.5 weight percent) was brought to light in the CF6 LPT blade program. Howmet vacuum arc re-melting (VAR) was unsuccessful in hitting the required range, as was Timet. At the time, the state of the art was ±3 wt% Al within the ingot. In order to mitigate this, GE developed a heat treatment that yielded relatively uniform mechanical properties in cast blades in spite of the wide variation in aluminum content from blade to blade. This allowed GE Aviation to make full sets of parts for the CF6 program. Subsequent work at Oremet-Wah Chang (now Allvac), using an internally developed VAR method, was shown to be capable of meeting GE's chemistry specification, and has been the method of choice for current production.

CF6 hardware was successfully produced, and GE ran 1,027 cycles in 286 hours of engine testing in the summer of 1993. The LPT module was disassembled, parts were inspected, and a decision was made to reinstall the gamma blades and run another block of engine testing consisting of another 502 cycles, which were successfully completed in 1994. This engine testing demonstrated that it was possible to manufacture, assemble, disassemble, inspect, reassemble, and run gamma TiAl LPT blades.

Subsequently, F414 seal support rings (1995-1996) and ESPR (Engineering Research Association for Supersonic Transport Propulsion System; Japanese government funding) shroud support rings (2002) were successfully produced and engine-tested. Production and engine testing of these three significantly different components significantly grew the organizational confidence needed to introduce gamma TiAl.

Government funding, in particular NASA and Navy contracts, greatly advanced GE's understanding of 48-2-2 and the practical capability of alternate alloy systems. Invention of NCG 359 (Navy cast gamma 359—the 359 is half of 718) helped in the understanding of the functional limitation of gamma alloys—especially crack growth rate, which was found to be difficult to enhance beyond 48-2-2. GE subsequently minimized the pursuit of other TiAl chemistries to focus on understanding Ti 48-2-2 behavior and application requirements.

1995-1996

NASA Enterprise Project Management contracts that produced large Ti 48-2-2 castings at Precision Castparts Corporation (PCC) generated welding procedures (resulting in the construction of the welding facility currently being used in production of the GEnx blades at PCC). NASA work on impact resistance and subsequent fatigue behavior was instrumental in defining blade leading-edge geometry and solidifying the GE design practice for LPT blades. Additionally, GE Aviation received a contract to develop a defect-tolerant design approach for Ti 48-2-2, called Damage Tolerant Design of Gamma (DTDG). All of this work was performed in the 1990s, contributed to the understanding of Ti 48-2-2, and was instrumental in defining blade leading-edge geometry and solidifying GE's design practice for LPT blades.

1997

In 1997, the GE90-115 reduced all of the above information into a complete design practice. Based on its Enterprise Project Management work, PCC was selected to work conventional casting processes. Cost targets were met on a projected basis, but due to the unknown risk of achieving the cost-versus-weight benefit, plus immaturity of the supply chain with respect to meeting aggressive engine development program commitments, implementation was not pursued.

1997-2004

During the 1997-2004 time frame, only Japan's ESPR funding kept gamma TiAl research alive at GE. Without this program, GE would not have been able to start the GEnx program in time for the first engine to test (FETT). PCC had an inventory of 8,000 pounds of GE Ti 48-2-2 that was not used for ESPR, and this material became the original stock used to rapidly start the GEnx program.

2004 to Today

After 2004, GE 48-2-2 was selected for the GEnx1B stage 6 and 7 LPT blades, launching the development of an overstock casting process at PCC, a full design database, machining studies, and implementation of a gamma LPT design practice at GE.

During the late 1990s, Air Force funding (Efficient Processing of Near-Gamma Titanium Aluminide) evaluated the cost-effectiveness of conventional forging, powder metallurgy, and casting for the producibility of several components and determined that casting was the most cost-effective route. Advances in forging and alternate casting processes have been made in the past 7 years, particularly in the European Union (EU), where significant government funding has been put into TiAl processing for both the gas turbine and automobile (turbochargers and valve) businesses. GE evaluated the current forging and powder processes and assessed casting as the best long-term cost approach for producing GEnx LPT blades. Future advances in manufacturing processes, including the industrialization of meltless TiAl, are needed to facilitate practical, cost-effective alternatives to casting. In the meantime, casting processes will be improved as well.

The lack of an established industrial base for the production of gamma TiAl has been the most significant impediment to implementation. The costs of the 20 years of GE R&D to understand the material, to develop the design practices, to conduct engine tests, and to certify TiAl are on the order of $40 million. The additional cost that GE has incurred to industrialize gamma TiAl LPT blades is in excess of $85 million.

E.1.2 Development of Gamma TiAl at Allison Gas Turbine

A range of Air Force and Navy contracts supported titanium aluminides technology development at Allison Gas Turbine (now Rolls-Royce North America, Inc.) in the 1980s through the early 2000s, including the following: Hot Rolling of TiAl Sheet; Turbine AF applications; Composite Disk Validation; Gamma Ti Aluminides Development; High Temperature Coatings for Ti Aluminides; Joining of Aluminides and Metal Matrix Composites; Damage Tolerant Design with Gamma; and Integrated High Performance Turbine Engine Technology (IHPTET) and Core and Engine Structural Assessment Research (CAESAR) demonstrators in the late 1990s and 2000s. Developments for NASA were cast gamma airfoils for regional engines in 1995.

In addition to these contracts, many development activities were funded by IR&D that led to the development of Alloy 7, which is one of the highest-strength and best-performing wrought TiAl alloys. The current generations of high Nb alloys at Rolls Royce are all based on the baseline Alloy 7 compositions. Most of the development work and understanding of gamma TiAl led to the development of compressor blades and vanes, and these were successfully tested in both Advanced Turbine Engine Gas Generator/Joint Technology Demonstrator (ATEGG/JTDE) and CAESAR test engines, but have not yet found production applications.

E.2 ALPHA-2 Ti_3Al DEVELOPMENT—LESS THAN EXPECTED POTENTIAL

As noted above, all successful materials possess one to several of the following criteria:

- Satisfies property and processing requirements,
- Technology pull matched technology push,
- Insertion timeliness meshed with application need,
- Strong systems pull,
- Amenable to modification to improve properties,
- Stable industrial base,
- Maturity—no major surprises,
- Key structure-property relationships understood,
- Industry willing to take risks,
- High confidence,
- No other material will work, and
- Adaptable/flexible properties and processing.

Meeting property requirements may seem to be an obvious minimum criterion. However, there are materials that are deficient in key properties but that are in routine use, in some cases in very demanding applications. This is possible if the property deficiencies can be overcome by establishing limits on the use of a material or by changing a design. For example, a material that does not have the required "time at temperature" capability may be used if a routine replacement of a component after a specified time interval is feasible. In other cases, design changes can compensate for material deficiencies and allow higher use temperatures or increased times at temperature. Unfortunately, there are penalties associated with compensating for the material. Limits on lifetimes can have major cost implications, and design changes can add weight and producibility issues.

Some materials, however, never transition into routine applications. Such materials may be so deficient that maintenance or design "work-arounds" are not feasible because the associated penalties are too severe. It is also possible that these materials' deficiencies are overcome by materials substitution; that is, an alternate material that meets the requirements becomes available. An example of a material that has not had a successful history is alpha-2 Ti_3Al.

When the National Aerospace Plane (NASP) project (Figure E.1) was initiated in the early to mid-1980s, speed and reusability were major drivers. The speed requirement would result in airframe temperatures reaching 1000°C over a large portion of the plane's surface, with leading edges reaching temperatures as high as 1650°C. The reusability requirement meant that time at temperature was also critical to the plane's mission. Consequently, both alpha-2 and gamma titanium aluminides were in the mix early as candidate airframe materials. Alpha-2 was considered the more promising candidate, offering higher ductility, higher tensile strengths across the entire temperature range, and processibility.

As the development cycle for the application of this material to NASP progressed, testing of the material in key environmental conditions was carried out. A key environmental requirement associated with reusability is properties at elevated temperatures in air over extended periods of time. The results of these tests revealed that alpha-2's oxidation resistance over time was unsatisfactory and was actually no better than high-temperature titanium alloys such as Ti-6242 or Ti-834.

FIGURE E.1 Artist's concept of National Aerospace Plane (NASP) vehicle. SOURCE: NASA.

Approaches to improving this key deficiency involved the addition of large amounts of expensive, relatively dense alloying elements, causing the material to become more expensive and heavier. In the final analysis, these changes did not yield a significant improvement in oxidation resistance. Consequently, two of its initially attractive features, weight savings and high-temperature properties, were not realized.

While the work on alpha-2 was yielding discouraging results, the gamma alloy continued to improve, especially with castings, to the point at which they had sufficient ductility to be considered for structural alloys. In addition, this material had a naturally higher specific stiffness and high-temperature oxidation resistance as compared with alpha-2.

As applications to high-temperature airframes were disappearing, applications to turbine engines would seem to have potential. Engine companies were requiring higher and higher temperature capability. Unfortunately, alpha-2's oxidation resistance and higher density made it unattractive for turbine engine applications. The risk-averse nature of the engine community was especially incompatible with this material's history.

In summary, after the investment of substantial resources, the initial potential of this material was never realized. It failed to meet several of the key criteria associated with the applications at the time, and an alternate material was improved to the point that it became the prime candidate. Eventually, the major airframe systems pull disappeared altogether owing to the cancellation of the NASP Program. Key deficiencies and competition from other materials also took it out of consideration for turbine engines.

E.3 NICKEL-BASED SUPERALLOY SUCCESS STORY

The characteristics of materials that successfully transition from development to application are not "universal." There is no set template that "fits all" materials. However, all successful materials do possess one to several of the criteria listed above (see Section E.2).

Superalloys are based on Group VIIIB elements, located within the transition metals section of the Periodic Table. The base metals are typically nickel, iron, and cobalt, with alloying additions of cobalt, chromium, nickel, iron, tungsten, aluminum, titanium, niobium, and tantalum. Superalloys based on nickel are the predominant materials in terms of commercial applications. They have been providing exceptional high-temperature properties and processing for more than 60 years. As early as World War II they were employed in critical high-temperature military applications. Over the ensuing years the number of applications greatly expanded, as did the amount of the alloys in existing applications. As discussed above, major advances in gas turbine engine performance were the direct result of increased temperatures, which in turn were made possible by improved materials. The hottest and most demanding applications in today's high-performance engines, the combustor and high-pressure turbine (Figure E.2), are dominated by nickel-based alloys. One of the major attributes of these materials is that their temperature capability has progressed steadily over the years, as shown in Figure E.2. This evolution in temperature capability has resulted from improvements in alloy composition and processing, from wrought, to conventionally cast, to directionally solidified, to single crystal. This progression in temperature capability has allowed the material to keep pace with the design. A key indicator of their success is that they now comprise over 50 percent of the weight of a high-performance turbine engine.

This class of alloys has been very successful because it possesses many of the characteristics of successful materials cited above: outstanding properties for many demanding applications (e.g., high specific properties, high-temperature mechanical and thermal stability, low-temperature ductility, and processability); no other materials will work (it is the only material that will provide the required properties for the combustor and turbine—the hottest and most demanding sections of a gas turbine engine); excellent adaptability/flexibility (an unparalleled ability to

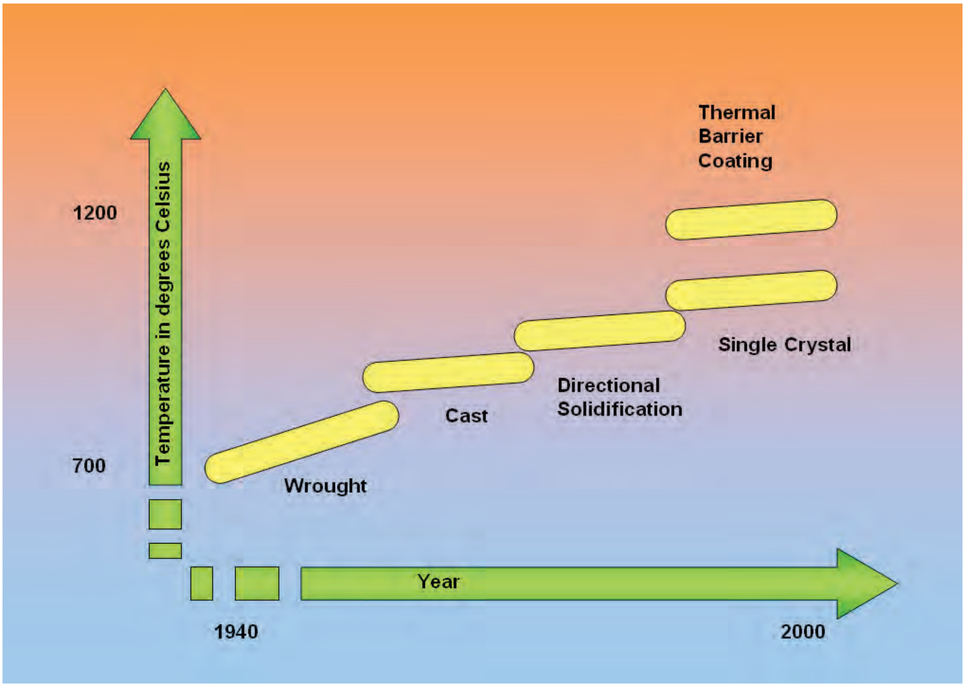

FIGURE E.2 Improvements in alloy temperature capability.

respond to the designer's desire for higher temperature, as shown in Figure E.2); a constant evolution of understanding how to provide the user with a high degree of confidence in the material; and no show-stoppers or major surprises.

To understand why these materials have been successful, one needs to understand the material's chemistry and chemical behavior. Nickel has no phase transformation between room temperature and its melting point. Its face-centered cubic structure is amenable to facile processing and alloying. For intermediate temperatures, it can be either solid-solution-strengthened or precipitation-strengthened-solid solution, and it can be precipitation-strengthened for high temperatures. There are a variety of compatible alloying element chemistries, including aluminum, chromium, cobalt, iron, and tungsten. In the case of nickel superalloys, there has been a tremendous synergy between scientific understanding and applications—scientific understanding of the relationships between microstructure and high-temperature properties, and applications that have benefited from this understanding in the form of improved materials and processes. This synergy has been a "perfect storm" for a successful story.

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Acronyms

ABET	Accreditation Board for Engineering and Technology
ADVENT	Advanced Versatile Engine Technology
AF	Air Force
AFB	Air Force Base
AFMC	Air Force Materiel Command
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AFRL/RX	Air Force Research Laboratory's Materials and Manufacturing Directorate
AFSB	Air Force Studies Board
AIAA	American Institute of Aeronautics and Astronautics
ARPA	Advanced Research Projects Agency
ASTM	American Society for Testing and Materials
ATD	advanced technology demonstration
ATEGG	Advanced Turbine Engine Gas Generator
BAA	broad agency announcement
BIAM	Beijing Institute of Aeronautical Materials
CA	collaborative agreement
CAESAR	Core and Engine Structural Assessment Research
CBRNE	chemical, biological, radiological, nuclear, and explosives
CFD	computational fluid dynamics

CMC	ceramic-matrix composite
CMS	computational materials science
CONUS	continental United States
COSMAT	Committee on the Survey of Materials Science and Engineering
C2I	command, control, and intelligence
C4ISR	command, control, communications, computers, intelligence, surveillance, and reconnaissance
DARPA	Defense Advanced Research Projects Agency
DDR&E	Director, Defense Research and Engineering
DOD	Department of Defense
DOE	Department of Energy
DS	directional solidification
EAR	Export Administration Regulations
EPM	Enabling Propulsion Materials program
ESASP	*European Space Agency Special Publication*
ESPR	Engineering Research Association for Supersonic Transport Propulsion System
EU	European Union
EuMaT	European Technology Platform on Advanced Engineering Materials and Technologies
FETT	first engine to test
FlowPAC	[University of Notre Dame's] Institute of Flow Physics and Control
FLTC	Focused Long Term Challenge
GE	General Electric
GEnx	GE next generation
GPR	government property right
GRC	[GE's] Global Research Center
HEETE	Highly Efficient Embedded Turbine Engine
HFIR	high flux isotope reactor
HHS	Department of Health and Human Services
HIP	hot isostatic pressing
HPC	high-pressure compressor
HPT	high-pressure turbine
HSCT	High Speed Civil Transport
HTAM	High Temperature Aerospace Materials
HTML	High Temperature Materials Laboratory

ICME	Integrated Computational Materials Engineering
IEEE	Institute of Electrical and Electronics Engineers
IHPRPT	Integrated High Payoff Rocket Propulsion Technology
IHPTET	Integrated High Performance Turbine Engine Technology
IMWG	IHPRPT Materials Working Group
IP	intellectual property
IPD	integrated product development
IPDT	integrated product development team
IR&D	industry research and development
IRAD	independent research and development
ISI	Institute for Scientific Information
ITAR	International Traffic in Arms Regulations
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JPO	Joint Program Office
JSF	Joint Strike Fighter
JTDE	Joint Technology Demonstrator
JTO	Joint Technology Office
LCF	low cycle fatigue
LPC	low-pressure compressor
LPT	low-pressure turbine
LRE	liquid rocket engine
M&P	materials and processes
MASAP	Materials and Structures Augmentation Program
MDO	multidisciplinary optimization
MEANS	Materials Engineering for Affordable New Systems
MRL	Materials Research Laboratory; manufacturing readiness level
MSE	materials science and engineering
NASA	National Aeronautics and Space Administration
NASIC	National Air and Space Intelligence Center
NASP	National Aerospace Plane
NDA	nondisclosure agreement
NDE	nondestructive evaluation
NMAB	National Materials Advisory Board
NRC	National Research Council
NSDD	National Security Decision Directive
NSF	National Science Foundation

OEM	original equipment manufacturer
ONR	Office of Naval Research
ORNL	Oak Ridge National Laboratory
OSD	Office of the Secretary of Defense
PA	patent
PCC	Precision Castparts Corporation
PM	powder metallurgy
PPB	powder-particle boundaries
QC	quality control
R&D	research and development
S&T	science and technology
SEMATECH	Semiconductor Manufacturing Technology
SOA	Service-oriented architecture
SRM	solid rocket motor
STOVL	short take-off and vertical landing
TBC	thermal barrier coating
TRL	technology readiness level
UAV	unmanned aerial vehicle
USAF	United States Air Force
USDA	United States Department of Agriculture
USML	United States Munitions List
VAATE	Versatile Affordable Advanced Turbine Engine
VAR	vacuum arc re-melting
VIAM	All-Russian Scientific Research Institute of Aviation Materials
VIM	vacuum induction melted