Benchmarking the Competitiveness of the United States in Mechanical Engineering Basic Research

Panel on Benchmarking the Research Competitiveness of the United States in Mechanical Engineering, National Research Council

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Benchmarking the Competitiveness of the United States in Mechanical Engineering Basic Research

Panel on Benchmarking the Research Competitiveness of the United States in Mechanical Engineering

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Panel on Benchmarking the Research Competitiveness of the United States in Mechanical Engineering

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This report has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that it meets institutional standards of 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:

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Although the reviewers listed above provided many constructive comments and suggestions, they did not see the final draft of the report before its release. The review was overseen by Dr. Maxine Savitz, Retired General Manager of Technology and Partnerships, Honeywell Inc, and Dr. C. Bradley Moore, Northwestern University. Appointed by the National Research Council, they were 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 authors and the institution.

Preface

At the request of the National Science Foundation Engineering Directorate, the National Academies performed an international benchmarking exercise to determine the standing of the U.S. research enterprise in the field of mechanical engineering relative to its international peers. This of course was no trivial undertaking, even for the panel of mechanical engineers assembled—11 members, mostly from U.S. universities, with expertise across the 11 selected areas of mechanical engineering covered in the report (see Chapter 1): acoustics and dynamics, bioengineering, computational mechanics, design and computer-aided design, dynamic systems and controls, energy systems, manufacturing and computer-aided manufacturing, mechanics of engineering materials, microelectromechanical systems and nanoelectromechanical systems, thermal systems and heat transfer, and tribology. The panel was charged with addressing three specific questions:

1. What is the current position of U.S. mechanical engineering research relative to that of other regions or countries?
2. What key factors influence U.S. performance in mechanical engineering?
3. On the basis of current trends in the United States and abroad, what will be the relative U.S. position in the near term and in the longer term?

At the same time, the panel was instructed to perform its charge in a short time frame and with a limited budget. Thus, in order to adequately respond to its charge, the panel had to limit the scope of the exercise to assessing the state of mechanical engineering basic research as determined by the open research literature, the opinions of its peers, and easily accessible data on U.S. human resources and research funding. Based on this slice of information, this benchmarking exercise attempts to provide a "snapshot" of the current status of the discipline and to extrapolate the future status based on current trends. The report does not make judgments about the relative importance of leadership in each area nor make recommendations on actions to be taken to ensure such leadership in the future.

Ward O. Winer, Chair
Panel on International Benchmarking of
Mechanical Engineering Research

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Summary

Mechanical engineering is critical to the design, manufacture, and operation of small and large mechanical systems throughout the U.S. economy. It is often called upon to provide scientific and technological solutions for national problems, playing a key role in the transportation, power generation, advanced manufacturing, and aviation industries, to mention a few. As pointed out in a 2002 National Science Foundation workshop,[1] "Today, the synergy of science and technology is producing an era of profound change. [Mechanical engineering] is intrinsic to this change through its impact on enabling technologies. These technologies include: micro- and nano-technologies, cellular and molecular biomechanics, information technology, and energy and environment issues."

Much like many other science and engineering disciplines, the field of mechanical engineering is facing issues of identity and purpose as it continues to expand beyond its traditional core into biology, materials science, and nanotechnology. Concerns about educating students, future employment opportunities, and the fundamental health of the discipline and industry are regular topics of discussion in the mechanical engineering community—for example, at meetings sponsored by the American Society of Mechanical Engineers (ASME) or the National Science Foundation.

STUDY BACKGROUND

Before addressing questions of how mechanical engineering must shift to meet future needs, it is imperative to understand its current health and international standing. At the request of the National Science Foundation Engineering Directorate, the National Academies performed an international benchmarking exercise to determine the standing of the U.S. research enterprise in the field of mechanical engineering relative to its international peers.

The field of mechanical engineering was benchmarked by an ad hoc panel consisting of 11 members, 10 from the United States and one from Canada, with expertise across the 11 selected areas covered in the report (discussed in Chapter 1): acoustics and dynamics, bioengineering, computational mechanics, design and computer-aided design (CAD), dynamic systems and controls, energy systems, manufacturing and computer-aided manufacturing, mechanics of engineering materials, microelectromechanical systems and nanoelectromechanical systems (MEMS/Nano), thermal systems and heat transfer, and tribology. The panel was charged with addressing three specific questions:

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[1] *New Directions in Mechanical Engineering*, Report from a Workshop Organized by the Big-Ten-Plus Mechanical Engineering Department Heads, Clearwater Beach, Florida, January 25-27, 2002, National Science Foundation.

1. What is the current position of U.S. mechanical engineering basic research relative to that of other regions or countries?
2. What key factors influence U.S. performance in mechanical engineering?
3. On the basis of current trends in the United States and abroad, what will be the relative U.S. position in the near term and in the longer term?

Following a process similar to that established in *Experiments in International Benchmarking of U.S. Research Fields*,[2] the panel was instructed to perform its charge in a short time frame and with a limited budget. The group met in person once and otherwise communicated by way of teleconference or electronic mail. Thus, in order to adequately respond to its charge, the panel had to limit the scope of the benchmarking exercise to assessing the state of basic (fundamental) research as determined by the open published literature, the opinions of its peers, and other sources of easily accessible information. This benchmarking exercise was conducted based on the premise that evaluating this type of more "academic" research information would give a good estimate of the quality and quantity of fundamental research being conducted, which could in turn be used as an indicator of the competitiveness of overall U.S. mechanical engineering basic research. Thus, this exercise in no way presents a complete picture of the research activity in the field—particularly the industrial component.

The quantitative and qualitative measures employed to compare U.S. mechanical engineering basic research with that in other nations included analysis of journal publications (numbers of papers, citations of papers, and most-cited papers), utilizing such sources as Thompson ISI Essential Science Indicators and Scopus. In addition, the panel asked leading experts from the United States and abroad to identify the "best of the best" whom they would invite to an international conference in their subfield. The national makeup of these "virtual congresses" provides qualitative information on leadership in mechanical engineering. The panel also examined trends in the numbers of degrees, employment, and research funding of U.S. mechanical engineering, relying heavily upon NSF *Science and Engineering (S&E) Indicators 2006* and earlier years.

The resulting report details the status of U.S. competitiveness in mechanical engineering basic research and its areas and subareas. This benchmarking exercise attempts to determine the current status of the discipline and to extrapolate the future status based on current trends. The report does not make judgments about the relative importance of leadership in each area or recommendations on actions to be taken to ensure such leadership in the future.

IMPORTANCE OF MECHANICAL ENGINEERING

Mechanical engineering is a discipline that encompasses a broad set of research areas. At the core of mechanical engineering are the design, analysis, manufacturing, and control of solid, thermal, and fluid mechanical systems—as well as, innovative application of technology, systems integration, creation and development of new products and markets, and solution to product problems. This includes optoelectrical-mechanical machines, materials, structures, and

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[2] Committee on Science, Engineering, and Public Policy, 2000, *Experiments in International Benchmarking of U.S. Research Fields,* National Academy Press, Washington, D.C.

micro- and nanoscale devices. Key aspects of the discipline also include heat transfer, combustion, and other energy conversion processes; solid mechanics (including fracture mechanics); fluid mechanics; biomechanics; tribology; and management and education associated with the above areas.

Medical research in particular is moving toward the molecular level, and rigorous mechanical engineering is central to future progress in medicine. Mechanical engineering plays a significant role in tissue engineering, medical instrumentation, prostheses, and medical devices.

Mechanical engineering will also play a central role in attaining energy independence. Almost all aspects of the national response to alternative energy issues involve mechanical engineering, including energy conversion, hybrid power, energy storage, and utilization of alternative fuels. Mechanical engineers are now working to develop sustainable energy sources including new photovoltaic devices.

Mechanical engineering also holds the keys to improving our environment. Mechanical engineers have developed cleaner, more efficient energy conversion systems and new materials from renewable or recycled resources. Mechanical engineers aim to develop highly selective, energy-efficient, and environmentally benign new synthetic methods for the sustainable production of energy and materials.

The dramatic growth in the use of computer methods for modeling and simulation of mechanical systems has had a profound impact on mechanical engineering, and the field of computational mechanics has become a vital component of this engineering discipline.

KEY FINDINGS AND CONCLUSIONS

The key findings and conclusions of the report are summarized below.

The United States is Among the Leaders in Mechanical Engineering Basic Research

Evidence for current research leadership in mechanical engineering basic research comes from analysis of journal articles, most cited articles, and virtual congresses by the panel (described in more detail in Chapter 2). Overall, the United States is among the leaders in mechanical engineering basic research. However, excellent mechanical engineers throughout the world provide stiff competition for the United States, especially in Asia and Europe.

- In 2002-2006 the United States published 24 percent of the mechanical engineering articles in the world. For 1987-1991, the U.S. contribution was 48 percent. A stiff competitor for numbers of publications is China, which published 7,580 articles in 2006, while the United States authored 5,660 articles.
- U.S. mechanical engineers contribute strongly as authors to the leading research journals in this field, accounting for about 40 percent of the articles and 40 percent of the most-cited articles in 68 selected journals.
- U.S. mechanical engineers contributed 65 or more out of the 100 most-cited articles in the Scopus database from 1987 to 2006.

- The combined virtual congress and journal analysis supports the conclusion that the United States is the leader or among the leaders in all areas of mechanical engineering basic research. The United States is

    - The leader in bioengineering, design and CAD, manufacturing/CAM, mechanics of materials , and thermal and heat transfer, with an average 50-70 percent U.S. contribution; and
    - Among the leaders in acoustics and dynamics, computational mechanics dynamics and controls, energy systems, and MEMS/nano tribology, with an average 30-50 percent U.S. contribution.

Overall, the United States is among the leaders in mechanical engineering basic research, with the following average contributions:

- 50 percent of virtual world congress (VWC) speakers,
- 40 percent of journal articles, and
- 40 percent of most-cited articles.

These results indicate that overall the United States is among the leaders in mechanical engineering basic research.

A Combination of Factors is Responsible for U.S. Basic Research Leadership in Mechanical Engineering

U.S. research leadership in mechanical engineering basic research is the result of a combination of key factors, including a national instinct to respond to external challenges and to compete for leadership. Over the years, the United States has been a leader in innovation as a result of cutting-edge facilities and centers, and a steady flow of mechanical engineers and research funding.

- Major centers and facilities provide key infrastructure and capabilities for conducting research and have provided the foundation for U.S. leadership. Key capabilities for mechanical engineering basic research include the following:

    - Measurement and standards
    - Materials characterization and micro- and nanofabrication
    - Manufacturing and automation
    - Biomechanical engineering
    - Supercomputing and cyberinfrastructure
    - Small- and large-scale fluid flow systems

- There is increasingly strong competition for international science and engineering human resources. Between 1997 and 2005, the number of U.S. citizens who received mechanical engineering Ph.D. degrees declined 35 percent. Nevertheless, the United States has maintained a steady supply of Ph.D. mechanical engineering graduates over the years. This has meant relying increasingly upon foreign-born students.

- Research funding for S&E overall and in mechanical engineering in particular has been steady. In 2005, more than $900 million was spent on mechanical engineering research and development (R&D) at academic institutions. Of this, about two-thirds consisted of federal expenditures. Federal support for U. S. mechanical engineering research between 1999 and 2003 was on average about 1 percent of the total U.S. R&D budget, with the largest portion (more than 70 percent) coming from the U.S. Department of Defense (DOD).

Challenges Lie Ahead for the Future Position of Mechanical Engineering Basic Research

The United States now holds a position among the leaders in most areas of mechanical engineering basic research, but because of the advance of mechanical engineering in other nations, competition is increasing and the U.S. lead will shrink. The United States is particularly strong in areas at the interface with other disciplines. In these areas, which include bioengineering, design, and mechanics of materials, the United States will maintain the leadership position in spite of growing competition. In some core areas where the U.S. position is currently not as strong, such as acoustics and dynamics, dynamics and controls, computational mechanics, and tribology, the U.S. position among the leaders may continue to fade.

On the basis of current trends in the United States and abroad, the relative future U.S. position in mechanical engineering basic research is outlined below:

- There will be growing industrial opportunities in China and India, which will result in increased mechanical engineering research talent and leadership abroad.
- There will likely be continued movement offshore of mechanical engineering R&D by U.S. companies, as well as increased competition from foreign companies. Local talent will be hired, which will likely include international students educated and trained in the United States.
- There will also be more international research collaborations (United States and other countries, between countries in the European Union, etc.).
- U.S. universities will continue to reach out and offer educational opportunities abroad and online. If the United States does not, other countries certainly will.
- Contemporary issues such as national security, energy, manufacturing competitiveness, and sustainability will be a strong influence on research directions in mechanical engineering. These are areas in which mechanical engineering can make significant contributions.
- Going forward, there will be a continued emergence of certain fields such as MEMS, nanotechnology, mechatronics, alternative energy sources, biomedical materials and devices, green manufacturing, and materials over many length scales. In addition, there will be continued importance of high-technology fields where the United States maintains a strong leadership position, such as the design and manufacturing of civilian and military aircraft, healthcare diagnostics, and power generating systems.
- U.S. academic mechanical engineering departments continue to attract international talent for graduate studies. However, the barriers to travel for international students and visiting

faculty may impact the ability of the United States to continue to attract this important source of U.S. mechanical engineering basic research talent.

CONCLUSION

U.S. leadership in mechanical engineering basic research overall will continue to be strong. Contributions of U.S. mechanical engineers to journal articles will increase, but so will the contributions from other growing economies such as China and India. At the same time, the supply of U.S. mechanical engineers is in jeopardy, because of declines in the number of U.S. citizens obtaining advanced degrees and uncertain prospects for continuing to attract foreign students. U.S. funding of mechanical engineering basic research and infrastructure will remain level, with strong leadership in emerging areas.

1

Introduction

Like many other fields of science and engineering, mechanical engineering is facing growing uncertainty about its research competitiveness. Concerns about educating students, future employment opportunities, and the fundamental health of the discipline and industry are regular topics of discussion in the mechanical engineering community, in venues such as meetings of the American Society of Mechanical Engineers (ASME) or at workshops of the National Science Foundation (NSF).[1] Mechanical engineering researchers seek to position the discipline to meet the needs of the future. However, before addressing future needs, it is imperative to understand the current health and international standing of the discipline.

KEY CHARACTERISTICS OF MECHANICAL ENGINEERING BASIC RESEARCH

Mechanical engineering is a discipline that encompasses a broad set of research areas. At the core of the discipline are the design, analysis, manufacturing, and control of solid, thermal and fluid mechanical systems. This now has expanded to include optoelectrical-mechanical machines, materials, structures, and micro- and nanoscale devices. Key aspects of the discipline also include heat transfer, combustion, and other energy conversion processes; solid mechanics (including fracture mechanics); fluid mechanics; biomechanics; tribology; and management and education associated with the above areas.

ROLE OF MECHANICAL ENGINEERING BASIC RESEARCH IN THE U.S. ECONOMY

Mechanical engineering is critical to the design, manufacture, and operation of small and large mechanical systems throughout the U.S. economy. It is often called upon to provide scientific and technological solutions for national problems, playing a key role in the transportation, power generation, manufacturing, and aviation industries, to mention a few.

According to the NSF workshop report *New Directions in Mechanical Engineering*, "In terms of both research areas and education, the mechanical engineering profession has been

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[1] *New Directions in Mechanical Engineering*, Report from a Workshop Organized by the Big-Ten-Plus Mechanical Engineering Department Heads, Clearwater Beach, Florida, January 25-27, 2002, and "5XME" workshop: Transforming Mechanical Engineering Education and Research in the USA, May 10-11, 2007.

instrumental in the birth and development of industries such as nuclear and aerospace, and has been the foundation of broad-based disciplines such as industrial engineering. Mechanical engineering has played, and continues playing, a commanding role in trends that drive change in engineering." As pointed out at a 2002 National Science Foundation workshop,[2] "Today, the synergy of science and technology is producing an era of profound change. Mechanical engineering is intrinsic to this change through its impact on enabling technologies. These technologies include: micro- and nano-technologies, cellular and molecular biomechanics, information technology, and energy and environment issues." For example, mechanical engineers are prominent in medical areas such as tissue engineering, instrumentation, prostheses, and medical devices and in energy areas such as energy conversion, hybrid power, energy storage, and utilization of alternative fuels. A mechanical engineering success story involves large reductions in pollutants from internal combustion engines and other combustion-related energy systems.

MECHANICAL ENGINEERING DEFINED FOR THIS REPORT

For the purposes of this report, the panel divided mechanical engineering into 11 areas, most with multiple subareas (see Box 1-1). This is not a comprehensive list, but rather provided a framework for the panel to assess the U.S. strength in modern mechanical engineering. The majority of the 11 areas have already been identified earlier in the discussion of key characteristics. Bioengineering, energy, and microelectromechanical systems and nanoelectromechanical systems (MEMS/Nano) represent active areas of research in modern mechanical engineering. The dramatic growth in the use of computer methods for modeling and simulation of mechanical systems has had a profound impact on mechanical engineering and it has affected every area of mechanical engineering. In particular, the field of computational mechanics has become a vital component of this engineering discipline, and the panel has identified it as an independent area.

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[2] *New Directions in Mechanical Engineering*, Report from a Workshop Organized by the Big-Ten-Plus Mechanical Engineering Department Heads, Clearwater Beach, Florida, January 25-27, 2002.

BOX 1-1 Areas and SubAreas of Mechanical Engineering in This Report

ACOUSTICS AND DYNAMICS
- Acoustics
- Dynamics

BIOENGINEERING
- Biomechanics of Auditory, Cardiovascular, Musculoskeletal, and Respiratory Systems
- Constitutive Modeling of Hard and Soft Tissues
- Molecular and Cellular Biomechanics
- Functional Tissue Engineering
- Biomaterials

COMPUTATIONAL MECHANICS
- Computational Fluid Dynamics
- Computational Solid Mechanics
- Computational Electromagnetics and Electromechanical Systems
- Computational Methods in Design and Optimization
- Computational Bio-Engineering

DESIGN AND COMPUTER AIDED DESIGN (CAD)
- Design Theory
- Design Modeling and Simulation
- Design Informatics and Environments
- Design Synthesis

DYNAMIC SYSTEMS & CONTROLS
- Modeling and Identification
- Control System Design Methodologies (Control Theories)
- Enabling Technologies
- Mechatronics and Applications
- Robotics and Automation

ENERGY SYSTEMS
- Renewable Energy Systems and Sources
- Energy Conversion
- Energy Storage
- Nuclear Energy

MANUFACTURING AND COMPUTER AIDED MANUFACTURING (CAM)
- Manufacturing Processes
- Manufacturing Tools and Equipment
- Manufacturing Systems
- Manufacturing Metrology
- Manufacturing Quality

MECHANICS OF ENGINEERING MATERIALS
- Nanomechanics and Nanomaterials
- Durability Mechanics
- Computational Materials
- Experimental Mechanics
- Multiscale Mechanics

MEMS/Nano
- Fundamental Issues
- Design and Modeling
- Micro/Nano Process Technologies
- Micro/Nano Devices and Systems

THERMAL SYSTEMS AND HEAT TRANSFER
- Combustion
- Heat Transfer
- Fluid Mechanics
- Nano/Micro Systems
- Applications

TRIBOLOGY
- Hydrodynamic Phenomena
- Friction and Wear
- Tribomaterials
- Contact Mechanics and Surface Engineering
- Diagnostics

STUDY CAVEATS

Because of the size and strength of U.S. science and engineering overall, in this report the United States is largely compared with regions, such as Europe or Asia, rather than with individual countries. On occasion, specific countries are discussed.

One difficulty in carrying out this benchmarking exercise was not being able to obtain data on international human resources (such as numbers of Ph.D.'s granted by country) and funding of mechanical engineering. Thus, the panel focused mainly on U.S. human resource and funding trends and relied on general science and engineering data to make international comparisons.

In addition, mechanical engineering is a highly diverse field, and mechanical engineers are employed in a broad range of industries. In some cases, mechanical engineers are not associated with mechanical engineering departments. As a result, the panel acknowledges that contributions from some individuals involved in mechanical engineering undoubtedly will not have been captured in this report.

ORGANIZATION OF THIS REPORT

The panel was instructed to perform its charge in a short time frame and with a limited budget, and followed a process similar to that established in *Experiments in International Benchmarking of U.S. Research Fields*,[3]. The group met in person once and otherwise communicated by way of teleconference or electronic mail. Thus, in order to adequately respond to its charge, the panel had to limit the scope of the benchmarking exercise to assessing the state of basic (fundamental) mechanical engineering research as determined by the open published literature, the opinions of their peers, and other sources of easily accessible information. This benchmarking exercise was conducted based on the premise that evaluating this type of more "academic" research information would give a good estimate of the quality and quantity of fundamental research being conducted, which could in turn be used as an indicator of the competitiveness of overall U.S. mechanical engineering research. Thus, this exercise in no way presents a complete picture of the research activity in the field—particularly the industrial component.

The quantitative and qualitative measures employed to compare U.S. mechanical engineering with that in other nations included analysis of journal publications (numbers of papers, citations of papers, and most-cited papers), utilizing such sources as Thompson ISI Essential Science Indicators and Scopus. In addition, the panel asked leading experts from the United States and abroad to identify the "best of the best" whom they would invite to an international conference in their subfield. The national makeup of these "virtual congresses" provides qualitative information on leadership in mechanical engineering. The panel also examined trends in the numbers of degrees, employment, and research funding of U.S. mechanical engineering, relying heavily upon NSF *Science and Engineering (S&E) Indicators 2006* and earlier years.

The outline of this report is as follows: Chapter 2 responds to the first question of the panel's charge and details the panel's assessment of the current standing of the United States in

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[3] Committee on Science, Engineering, and Public Policy, 2000, *Experiments in International Benchmarking of U.S. Research Fields,* National Academy Press, Washington, D.C.

the 11 areas of mechanical engineering. Chapter 3 addresses the second question of the charge and identifies the key determinants of leadership in the field. Chapter 4 addresses the third part of the charge, assimilating past leadership determinants and current benchmarking results to predict future U.S. leadership.

2

Current U.S. Leadership Position in Mechanical Engineering Basic Research

To determine the overall position of U.S. basic research in mechanical engineering relative to research performed in other regions or countries, the panel analyzed journals (paper authorship, most-cited journals, and journal articles) and panel-generated virtual congresses, which are described in more detail later in this chapter. The panel used the collective results of all of these data to draw conclusions of the relative research competitiveness of U.S. mechanical engineering. The panel tried to interpret the gathered information objectively, but it also recognized its responsibility to make collective subjective judgments when needed. In addition, certain boundaries were needed to keep the exercise timely and relevant to the broader mechanical engineering community.

The assessment of U.S. mechanical engineering research begins with a look at U.S. contributions to journal articles and most-cited journal articles. This is then followed by the virtual congresses, which were tabulated by the committee based on input from experts in mechanical engineering around the world. Finally, the panel provides leadership assessments for the different areas of mechanical engineering based on the journal and virtual congress data presented earlier in the chapter.

JOURNAL ARTICLES AND CITATIONS

Publishing research results is essential for scientific and technological progress. Thus, looking at the quantity and quality of journal articles being published in the world is an important and largely objective measure of scientific and engineering research leadership. For this analysis, the panel conducted broad literature searches as well as more targeted searches of specific mechanical engineering journals using the Scopus[1] database. Given the broad range of journals in which mechanical engineers publish, and in an effort to assess current trends in the directions of mechanical engineering research, the panel selected the journals as follows:

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[1] Scopus (*www.info.scopus.com*) is an Elsevier product that indexes "over 15,000 peer-reviewed health, life, physical and social science journals from more than 4,000 international publishers. Similar search results may be obtained using the Web of Science (*www.isinet.com/products/citation/wos*), which is a comparable science journal indexing product from the Thompson Corporation that was not available to the panel.

- Journals with broad coverage of mechanical engineering (e.g., *ASME Journal of Applied Mechanics*)
- Leading journals for each subarea of mechanical engineering:
    - Area-specific journals in which researchers from various sciences and/or engineering disciplines publish, along with researchers from mechanical engineering., (e.g., *Journal of Power Sources*)
    - Area-specific journals where mechanical engineering researchers are the primary contributors, e.g. *Journal of Fluid Mechanics*

The full list of 68 mechanical engineering-related journals considered by the panel, including impact factors[2] and country of publication, is given in appendix Table C-1. The journals in that list include high profile journals with high impact factors, as well as journals important to subareas of mechanical engineering but that may have low impact factors.

The panel largely focused its analysis of journal publications data on the change in publication rates and citations over roughly the 10 years 1995-2005, with particular attention paid to the change in the percentage of contributions from U.S. researchers.

Decreasing Overall U.S. Share of S&E Journal Articles

Examination of the number of articles published annually in the broader scientific literature on a regional basis shows that the profile of scientific activity worldwide has changed dramatically over the 15 years from 1988 to 2003 (Figure 2-1).[3] The long-standing scientific dominance of the United States persists, but other areas of the world are closing the gap.[4] In 1988, the United States was the largest contributor to S&E publications, even when compared to other regions. While the absolute number of U.S. S&E articles grew by 19 percent between 1988 and 2003, the output of articles from Western European nations combined increased by 67 percent and surged past the U.S. total. Dramatic growth was seen for articles from Korea (1,683 percent), China (630 percent), and Taiwan (556 percent). The percentage of articles coming from Asia and the subcontinent as a whole, which include China and India, have almost tripled in going from 4 to 10 percent. The percentage of all S&E articles from U.S. authors dropped from 38 percent to 30 percent between 1988 and 2003.

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[2] Impact factors were obtained from *2006 Journal Citation Reports*®. More information about impact factors can be found on the Thompson Scientific Website at: *http://scientific.thomson.com/free/essays/journalcitationreports/impactfactor/* (accessed September 10, 2007).

[3] These are the most recent numbers provided, in the *NSF Science and Engineering Indicators 2006*.

[4] "Asia 13" includes Bangladesh, China (including Hong Kong), India, Indonesia, Malaysia, Pakistan, the Philippines, Singapore, South Korea, Sri Lanka, Taiwan, Thailand, and Vietnam.

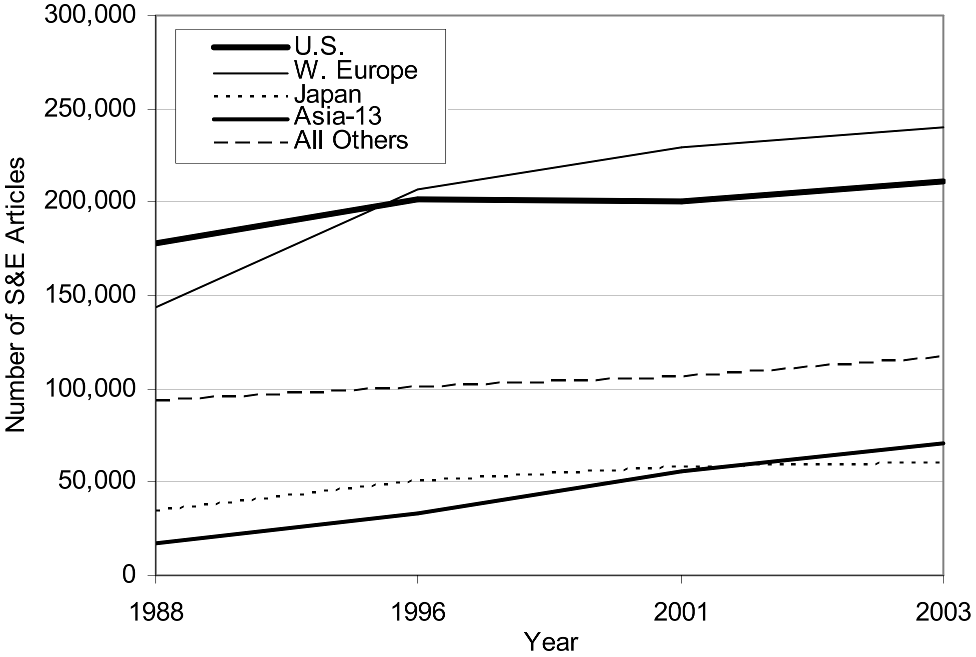

FIGURE 2-1 Numbers of all S&E articles for select countries and regions.
NOTES: Publication counts from set of journals classified and covered by Science Citation Index and Social Sciences Citation Index. Articles assigned to region/country/economy on the basis of institutional address(es) listed in article. Articles on fractional-count basis; i.e., for articles with collaborating institutions from multiple countries/economies, each country/economy receives fractional credit on the basis of proportion of its participating institutions.
"Asia 13" includes Bangladesh, China (including Hong Kong), India, Indonesia, Malaysia, Pakistan, the Philippines, Singapore, South Korea, Sri Lanka, Taiwan, Thailand, and Vietnam.
SOURCE: Regional and country portfolio of S&E articles, 1988, 1996, 2001, and 2003. *NSF Science and Engineering Indicators*.

U.S. Share of Mechanical Engineering Journal Articles

The panel conducted a literature search of the full catalog of journals in the Scopus database[5] using the search term "mechanical" in the author affiliation or source title to get a count of numbers of journal articles published for the period1988-2006. Based on these data, the panel found that the trend for the U.S. share of mechanical engineering journal articles is similar to the overall trend for S&E. Table 2-1 shows that the U.S. percentage contribution dropped from 40 percent for 1988 to 20 percent in 2006. In comparison, China's contribution increased dramatically from 2 percent in 1988 to 23 percent in 2006 (Figure 2-2). In 2006, China published more mechanical engineering articles than the United States, with 9,043 articles, while the United States authored 7,823 articles.

TABLE 2-1 U.S. Share of Worldwide Mechanical Engineering Journal Articles, 1988-2006

		U.S. Articles		China's Articles	
Year	Total No. of Articles	No.	%	No.	%
1988	5,123	2,071	40	100	2
1989	5,318	2,015	38	125	2
1990	5,912	2,720	46	109	2
1991	6,444	2,844	44	117	2
1992	4,995	3,083	62	110	2
1993	7,804	3,775	48	129	2
1994	7,864	3,515	45	125	2
1995	8,275	3,686	45	117	1
1996	14,276	5,680	40	415	3
1997	14,395	5,628	39	489	3
1998	12,822	5,130	40	537	4
1999	12,329	4,872	40	696	6
2000	12,956	4,433	34	842	6
2001	17,663	5,193	29	1,957	11
2002	20,250	6,036	30	1,598	8
2003	21,430	5,716	27	1,688	8
2004	25,499	5,577	22	2,510	10
2005	33,542	7,198	21	6,249	19
2006	38,952	7,823	20	9,043	23

SOURCE: Scopus database (*http://www.scopus.com/scopus/home.url*) search of "mechanical" in source title or author affiliation, and country in author affiliation.

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[5] *http://www.scopus.com/scopus/home.url*, accessed May 8, 2007.

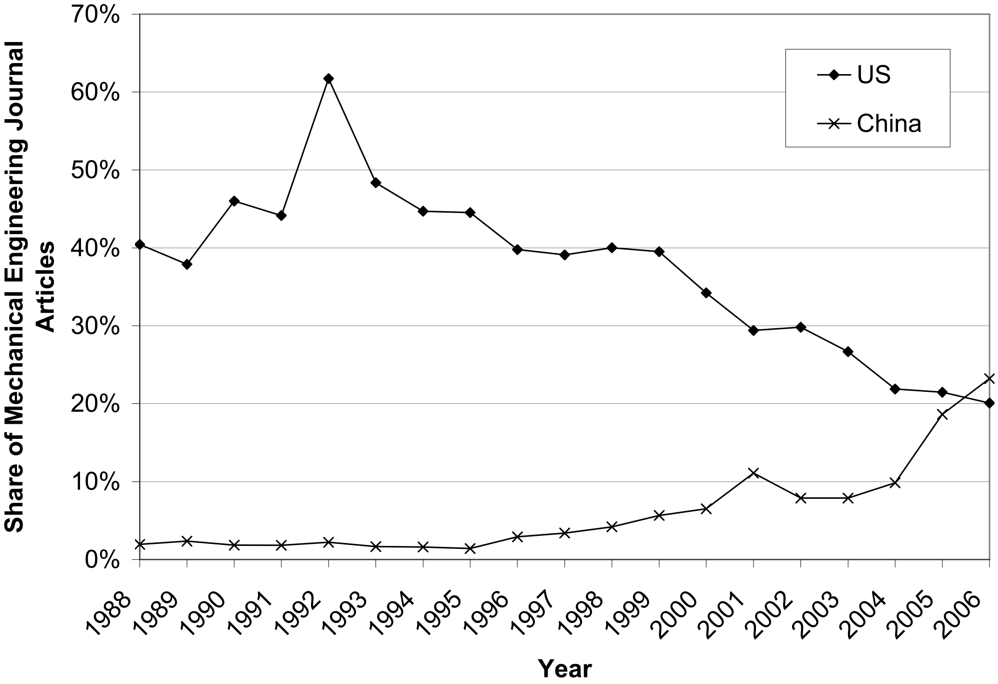

FIGURE 2-2 Comparison of U.S. and China's percentage share of contributions to overall mechanical engineering journal articles, 1988-2006.
SOURCE: Scopus database (*http://www.scopus.com/scopus/home.url*) search, "mechanical" in source title or author affiliation, and country in author affiliation.

Although the number of articles published by China and the United States are comparable, the journal titles where these two countries publish most of their research are quite different from each other (Table 2-2). Most of the journals in China's list are Chinese-language journals such at *Jixie Gongcheng Xuebao* (Chinese Journal of Mechanical Engineering), not indexed in the *2006 Journal Citation Reports*® (*JCR*). On the other hand, the U.S. journals are U.S. or European based English-language journals with international editorial boards. All but one of the journals in the U.S. list are listed in *JCR*, and with impact factors of more than 1. China does have a growing number (currently 75) journal titles across various disciplines listed in *JCR*.

TABLE 2-2 Comparison of Mechanical Engineering Journal Titles where China and the United States Published the Largest Number of Articles in 2006.

China		**United States**	
Journal	Article Count	Journal	Article Count
Zhongguo Jixie Gongcheng (China Mechanical Engineering)	843	*Journal of Fluid Mechanics*	102
Jixie Gongcheng Xuebao (Chinese Journal of Mechanical Engineering)	556	*International Journal of Heat and Mass Transfer*	89
Jixie Qiandu (Journal of Mechanical Strength)	192	*Journal of Mechanical Design Transactions of the ASME*	86
Run Hua Yu Mi Feng (Lubrication Engineering)	188	*Materials Science and Engineering A*	78
Wuhan Ligong Daxue Xuebao (Journal of Wuhan University of Technology)	133	*Physics of Fluids*	76
Chinese Journal of Mechanical Engineering English Edition	132	*Journal of Sound and Vibration*	76
Shanghai Jiaotong Daxue Xuebao (Journal of Shanghai Jiaotong University)	121	*Journal of Micromechanics and Microengineering*	60
Zhendong Ceshi Yu Zhenduan(Journal of Vibration Measurement and Diagnosis)	92	*Journal of Power Sources*	60
Xitong Fangzhen Xuebao (Journal of System Simulation)	85	*Journal of Biomechanics*	58
Frontiers of Mechanical Engineering in China	83	*Combustion and Flame*	57
Total	7,580	Total	5,660

SOURCE: Scopus database search, “mechanical” in source title or author affiliation, and country in author affiliation.

At the same time, U.S. contributions to top international mechanical engineering journals have remained quite steady over the last five years (1999-2005). From a list of 68 journals analyzed (see appendix Table C-2), the average U.S. contribution to mechanical engineering journal articles remained at around 40 percent between 1999 and 2005, with some mechanical engineering areas having significantly higher contributions from U.S. authors. Figure 2-3 (ranked from highest to lowest percentage U.S. contribution) shows the breakdown for journals according to year and area of mechanical engineering.

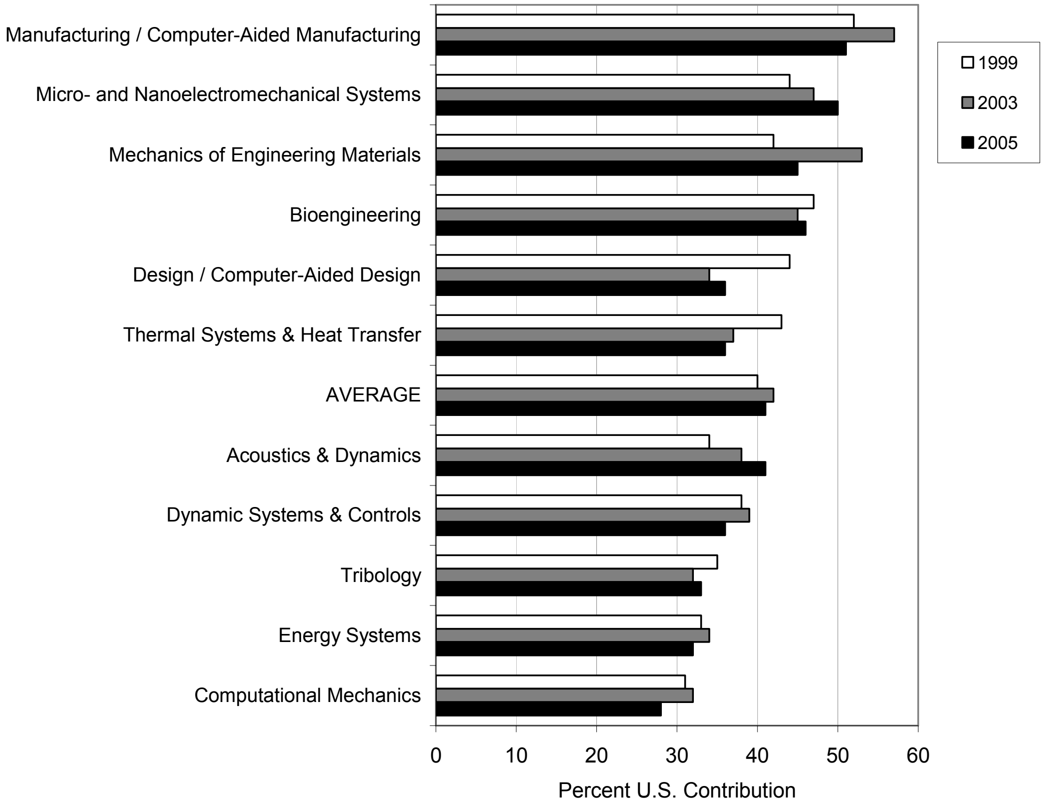

FIGURE 2-3 Percentage of U.S. contribution to 68 select journals (see appendix Table C-2) in areas of mechanical engineering, for select years 1999, 2003, 2005.

Steady U.S. Share of Most-Cited Articles

Journal article citations provide a better gauge of research leadership than numbers of articles. At the same time, counting citations is somewhat limited, since high citation counts often result from important past research results rather than current results. Nevertheless, this information on U.S. contributions to most-cited articles was obtained in two different ways in order to identify contributions to mechanical engineering. First, the Scopus database was used to determine the 50 most-cited articles for the 12 area-representative mechanical engineering journals (appendix table C-2), by year and country authorship. The average of the individual journal results (appendix Table C-3) show that U.S. authors contributed to 40-50 percent of the most-cited articles in these journals for all six years (Figure 2-4).

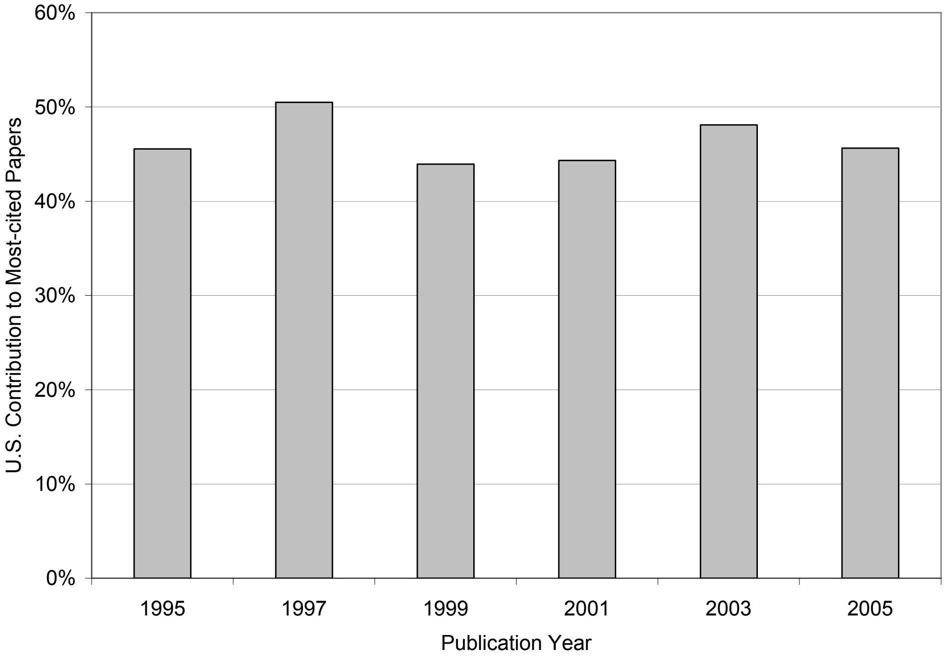

FIGURE 2-4 Average percentage contribution of most-cited mechanical engineering articles by U.S. authors out of the 50 most-cited mechanical engineering articles.

In a slightly different approach, the Scopus database was used to search for "mechanical" in the author affiliation or source title in all journals indexed for the periods 1987-1991, 1992-1996, 1997-2001, and 2002-2006. The top 100 most-cited articles from these periods were then searched for country of authorship to determine the U.S. contribution. Table 2-3 provides a summary of the results, showing the clear leadership position of the United States with 65 or more out of 100 articles over these times.

TABLE 2-3 U.S. Contribution to Most-Cited Mechanical Engineering Articles

Time period	Total No. of Articles	No. with U.S. Affiliation among Top 100 most-cited	Maximum cites (article #1)	Minimum cites (article #100)
1987-1991	26,694	65	401	50
1992-1996	41,163	82	955	90
1997-2001	69,753	84	1,356	116
2002-2006	134,453	78	329	60

The journal titles of the top 100 most-cited articles for each period were also sorted in order to evaluate mechanical engineering area contributions. Journals appearing in the top 100 three or more times are listed in Table 2-4.

Overall, bioengineering, thermal systems and heat transfer, computational, and materials-related journals figure prominently among the lists. As expected, the most recent list for 2002-2006, largely includes nanotechnology, materials, and biologically focused articles in journals such as *Acta Materialia* (5), *Nano Letters* (5), and *Science* (5). However, the journal at the top of the list for this time period, with 6 articles out of the top 100, is the *International Journal of Heat and Mass Transfer* (all U.S. authored).

TABLE 2-4 Journals with 3 or More Most-Cited Articles Appearing in Lists of 100 Most-Cited Mechanical Engineering Articles: 1987-1991, 1992-1996, 1997-2001, and 2002-2006

No. of Articles			No. of Articles			No. of Articles			No. of Articles		
Total	U.S.	1987-1991	Total	U.S.	1992-1996	Total	U.S.	1997-2001	Total	U.S.	2002-2006
17	2	*Philosophical Magazine A*	7	5	*Journal of Biomechanics*	5	5	*Journal of Fluid Mechanics*	6	6	*International Journal of Heat and Mass Transfer*
14	14	*Journal of Biomechanics*	5	4	*Automatica*	5	4	*Physical Review Letters*	5	3	*Acta Materialia*
9	9	*Journal of Biomechanical Engineering*	4	2	*Combustion and Flame*	4	4	*Journal of Computational Physics*	5	5	*Nano Letters*
4	2	*Combustion and Flame*	4	4	*Journal of Computational Physics*	3	3	*Annual Review of Fluid Mechanics*	5	4	*Science*
4	2	*International Journal of Mechanical Sciences*	4	4	*Science*	3	3	*International Journal for Numerical Methods in Engineering*	4	0	*Chemical Physics Letters*
4	2	*Journal of Orthopaedic Research*	3	3	*Atmospheric Environment*	3	3	*Journal of Microelectromechanical Systems*	4	3	*Langmuir*
4	2	*Spine*	3	2	*Journal of Fluid Mechanics*	3	3	*Metallurgical and Materials Transactions A*	3	1	*Biomaterials*
3	3	*Atmospheric Environment*	3	3	*Journal of Mechanical Design, Transactions of the ASME*	3	2	*Philosophical Magazine A*	3	2	*Composites Science and Technology*
3	1	*Automatica*	3	3	*Physical Review Letters*	3	2	*Physical Review B*	3	3	*Journal of Microelectromechanical Systems*
3	3	*Journal of Computational Physics*							3	3	*Journal of the Mechanics and Physics of Solids*
3	2	*Journal of the Acoustical Society of America*							3	2	*Polymer*

VIRTUAL WORLD CONGRESS

In another effort to evaluate the status of U.S. leadership in mechanical engineering, the panel called on an international group of leaders in the field for their qualitative assessment of the areas and subareas of mechanical engineering. This exercise is referred to as the virtual world congress (VWC), and it is based on the experience of past benchmarking panels.[6] To carry out the exercise, the field of mechanical engineering was divided into 11 major areas—and each area was subdivided into 2-5 subareas. The panel members individually identified 8-10 respected leaders throughout the world in each subarea. The selected organizers (listed in Appendix D) were asked to imagine that they were about to organize a VWC on the subarea topic; then, regardless of travel costs, visa restrictions, or the opinions of their peers, they were asked who would be the 10-20 speakers that must be a part of the imaginary session. A summary of the area results of the VWC (percentage of U.S. speakers chosen by area) presented in Figure 2-5. A detailed tabulation of the VWC results is given in appendix Table D-1. U.S. representation ranges from a high of 80 percent in the area of design and computer-aided design (CAD) to a low of 48 percent in the area of tribology. This is likely influenced by the origin of the VWC organizers (see Figure D-1). Overall about 70 percent of the VWC organizers were from the United States, and as expected, U.S. organizers were biased toward choosing U.S. speakers. U.S. organizers selected an average of 67 percent U.S. speakers, whereas non-U.S. organizers selected an average of 43 percent U.S. speakers. Also, because the VWC representation is largely populated by researchers with well-established reputations resulting from a long career, U.S. domination probably reflects past rather than present leadership.

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[6] Committee on Science, Engineering, and Public Policy, 2000, Experiments in International Benchmarking of U.S. Research Fields, National Academy Press, Washington, D.C.

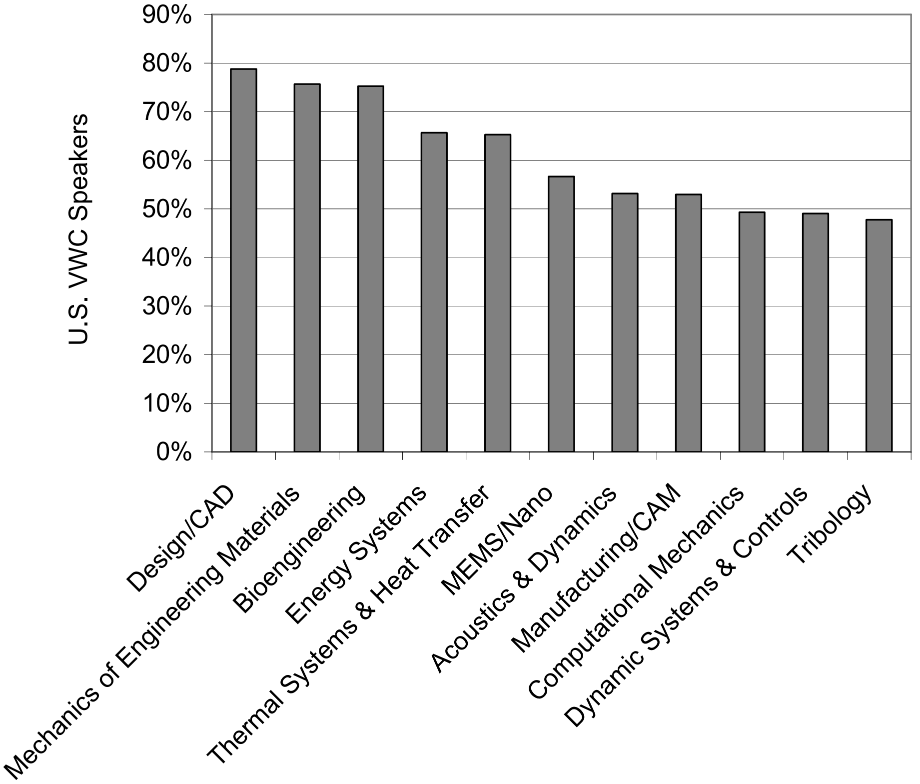

FIGURE 2-5 Summary of the percentage of U.S. speakers for the 11 areas of mechanical engineering, as determined by virtual world congress organizers.

MECHANICAL ENGINEERING AREA ASSESSMENTS

The panel also qualitatively evaluated the different areas and subareas of mechanical engineering, and made assessments of leadership based on the combined analysis of journal citations and VWC results. U.S. leadership was determined based on the criteria shown in Box 2-1.

BOX 2-1 Criteria for Determining Research Leadership

Greater than 70 percent U.S. contribution—the United States is the strong leader
Greater than 50 percent U.S. contribution—the United States is the leader
Greater than 30 percent U.S. contribution—the United States is among the leaders
Less than 30 percent U.S. contribution—the United States is lagging behind the leaders

Acoustics and Dynamics

Acoustics and dynamics both deal with time-dependent phenomena that are ubiquitous in nature as well as in the designed objects of our technologically based world. Acoustics is the engineering and science of fluid oscillations that lead to perceived sound or noise (if the sound is unwanted). Dynamics is the study of motion of mechanical objects as they may occur in nature (e.g., birds, trees) or as constructed (e.g., aircraft, automobiles, spacecraft).

To assess the current status of U.S. contributions in acoustics and dynamics, the following representative subareas were examined:

- **Nonlinear Phenomena.** Current research and (to an increasing extent) practice deal with large or nonlinear motions of very complex systems with many (perhaps millions of) degrees of freedom. Motions at small scales such as nanodevices and phenomena, so-called micro air vehicles, and MEMS devices are now more often the applications of interest.

- **Complex Systems.** Complex systems that involve a large number of degrees of freedom as may arise in computational models of fluid, structural, and molecular systems. Complex systems also arise due to the interaction of multimedia such as fluids interacting with structures or multiscale systems ranging from quantum to molecular to continuum models.
- **Computational Models.** Modeling the large variety of nonlinearities that arise in fluids and solids, constructing computationally efficient models of systems with many degrees of freedom, and multiscale modeling of events at the nanoscale are current major research challenges.
- **Experimental Methods.** Experimentally measuring the acoustic fields and dynamic response of complex nonlinear systems at very large to very small scales is also a major goal of current research.

Assessment

An average of 50 percent of the 303 VWC speakers selected in the area of acoustics and dynamics were from the United States. In the subareas, there was a 60 percent U.S. contribution in dynamics and a 41 percent U.S. contribution in acoustics.

The U.S. contribution to journal articles and article citations is more mixed. In 2005, the U.S. contribution to most-cited articles in the *Journal of Sound and Vibration* was 44 percent. The U.S. contribution is greater than 50 percent in U.S.-based ASME and Acoustical Society of America (ASA) journals, but 30 percent or lower in the internationally based *Journal of Sound and Vibration* and *Journal of Fluids and Structures*. Between 1999 and 2005, the average percentage U.S. contribution to articles published in acoustics and dynamics journals increased from 34 to 41 percent. Based on the combined analysis of journal citations (30-50 percent U.S.) and VWC data (50 percent U.S.), the United States is among the leaders in acoustics and dynamics basic research.

Biomechanics and Bioengineering

The field of biomechanics is concerned with motion, deformation, and forces in biological systems. Initially the field of biomechanics developed from contributions by experts trained in fields as diverse as auditory mechanics, cardiovascular mechanics, hemodynamics, musculoskeletal bioengineering, neuromuscular control and respiratory mechanics, and mechanism of propulsion for animal locomotion (walking, running, flying, and swimming). The first journal specializing in bioengineering appeared in the mid-1960s with the publication of the *Journal of Biomechanics* in 1965, which was followed by the ASME *Journal of Biomechanical Engineering* in 1976. Since then, biomechanical engineers have been at the forefront of medical device developments with tremendous clinical implications ranging from heart valves (e.g., the DeBakey-Noon heart pump), to artificial joints and more recent work on functional tissue engineering constructs, as well as pioneering multiscale and hierarchical strategies to connect physiologic function to cellular and molecular mechanisms. The diverse field of biomechanics may be subdivided into the following areas:

- **Biomechanics of auditory, cardiovascular, musculoskeletal, and respiratory systems.** Involves in vivo, in vitro, and computational studies of the electrical and mechanical function of physiological systems.
- **Constitutive modeling of hard and soft tissues.** Has to do with the development of physical models that represent tissue-microstructure and related biophysical processes, largely for clinical applications.
- **Molecular and cellular biomechanics.** Deals with understanding mechanical processes in organisms at the microsopic level, such as mechanosensitivity of bone cells to fluid shear stress.
- **Functional tissue engineering.** Involves repairing or replacing tissues that provide mechanical physiological properties.
- **Biomaterials.** Deals with the development of physiologically compatible materials, which are largely used in medical devices and implants.

Assessment:

An average of 75 percent of the 194 VWC speakers in the area of bioengineering and biomechanics came from the United States. These overall results are also consistent with those obtained from the chemical engineering panel,[7] which had significant overlap of both VWC organizers and speakers with the mechanical engineering panel.

The share of U.S. contributions to journal articles is somewhat different. U.S. contributions to the most-cited articles in *Biomaterials* ranged from 20 to 40 percent between 1995 and 2005. As shown in Table 2-4, the most-cited mechanical engineering journal articles for the periods shown included a significant number of bioengineering journals—which are largely U.S. authored. Five bioengineering journals that currently have the top five greatest impact factors—*Biomaterials*, *Journal of Orthopaedic Research*, *Journal of Biomedical Materials Research*, *Journal of Biomechanics*, and *Annals of Biomedical Engineering*—were examined. In addition, from 1999 to 2005, U.S. authors consistently provided roughly 40 to 45 percent of the content of these journals.

When taken in combination, the overwhelming virtual congress results (75 percent U.S.) and the relatively stable publications rate in the top bioengineering journals (40 percent U.S.),

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[7] National Research Council, 2007, *International Benchmarking of U.S. Chemical Engineering Research Competitiveness*, National Academies Press, Washington, D.C.

the United States can be considered the leader in the area of bioengineering and biomechanics basic research.

Computational Mechanics

Computational mechanics is concerned with the use of numerical methods and computer devices to study and predict the behavior of mechanical systems. Computational mechanics is a vital area of mechanical engineering, making possible the analysis, design, and optimization of systems at a level of sophistication not attainable by other means. At present, a large list of vital new technologies is on the horizon that will rely on advances in computational mechanics. These include new computational paradigms for nanomanufacturing design of new materials, patient-specific predictive surgery, drug design and delivery, weather and climate prediction, pollution remediation and detection and control of toxic agents, optimal design of mechanical systems, and many more. The successful development of a new generation of computer simulation tools that will make possible these technological advances will require substantial research efforts.

While it can be argued that the field of computational mechanics began in the United States in the 1950s and 1960s, substantial early work was also conducted in the United Kingdom and Germany. Important developments came later in France and Japan, and new work and engineering applications occur worldwide. The major components of computational mechanics are (1) computational and applied mathematics, (2) modeling (including the development of algorithms software, and (3) computing, including the development of computational devices that enable large-scale computations; data storage, retrieval, and distribution; and the use of computational grids

The major subareas of computational mechanics are computational fluid dynamics (CFD) and computational solid mechanics (CSM). Significant work in other subareas also exists, including computational electromagnetics, optimization, and biomedicine. These subareas of computational mechanics are described below:

- **Computational fluid dynamics.** Includes the study of turbulent flow, combustion modeling, compressible flow and aerodynamics, multiphase flow, flow in porous media, rarified gas dynamics, and kinetic theory.
- **Computational solid mechanics.** Includes the fields of computational materials, computational structural mechanics, impact dynamics, penetration mechanics, geosciences, and geotechnical engineering.
- **Computational electromagnetics and electromechanical systems.** Has to do the with modeling of electromagnetic phenomenon in mechanical systems, such as guided waves, radiation, and scattering.
- **Computational methods in design and optimization.** Include operations research, mechanical design, inverse analyses, control, and optimization.
- **Computational bio-engineering:** Involves computational methods applied to biomechanical systems.

Assessment

An average of 49 percent of the 489 VWC speakers for this area was from the United States. The percentage of most-cited articles in the *International Journal for Numerical Methods in Engineering* averaged 50 percent between 1995 and 2005. At the same time, only one-third of the articles written in 2005 were by U.S. authors, down from an estimated 50 to 60 percent in the 1980s. The percentage of articles by U.S. authors in two leading computational mechanics journals *International Journal of Numerical Methods in Engineering* and *Computer Methods in Applied Mechanics and Engineering* has been around 33 percent for several years. Overall, the United States is among the leaders in computational mechanics research, and decreases in the share of U.S. contributions to journal articles indicate that the margin of leadership is diminishing.

Design and Computer-Aided Design

Design in mechanical engineering involves a number of diverse topics, all related to the process of developing and producing products, systems, processes, and infrastructures. This includes fundamental theories underlying product realization processes and the types of decisions that are made in a design process, issues in the modeling and simulation of systems, challenges in the synthesis and optimization of systems, and emerging topics in design informatics and environments.

A holistic view of design is where a total system, life-cycle context recognizes the need for advanced understanding of the process of innovation, the identification and definition of preferences, the evaluation of alternatives, the effective accommodation of uncertainty in decisionmaking, and the relationship between information and knowledge in a digitallysupported design process. Mechanical engineering design in the United States is especially strong. However, this strong leadership across all areas of design is beginning to diminish, as Germany, France, England, Japan, Korea, China, and Australia each gain ground, while other European nations are also establishing themselves as leading authorities in specific areas of design.

The subfields within design have been identified by examining both the historical foundations of the field of design and the modern research areas that are both defining and shaping this dynamic field.

- **Design Theory.** Includes some of the basic pillars and frameworks of design and the types of models and decisions that are necessary in a design process. It includes research in the realm of "design for" capabilities, including studying system architecting and platforming. In addition, underlying research in the divergent and convergent processes underlying any design process is critical. Lastly, validation of these models and developments lies at the core of the research in design theory to effectively support fundamental decisions in design.
- **Design Modeling and Simulation.** Includes the vast scientific challenges underlying the approaches to the geometric and analytical modeling of design artifacts and processes. In addition, a number of more recent theoretical, experimental, and computational topics in multiscale and distributed modeling of systems are germane to this subfield. As system complexity increases, there is a need to move beyond deterministic models and

incorporate uncertainty and risk in design models, including adeptly developing appropriate surrogate modeling approaches.

- **Design Informatics and Environments.** Includes the growing research challenges involved in capturing, representing, and manipulating the information and knowledge that is inherently woven throughout design processes. It includes information technology areas such as cyberinfrastructure development and design, digital libraries, and ontologies and human-computer interaction areas such as visualization, haptics, and web environments.
- **Design Synthesis.** Includes the research challenges in design optimization such as inverse methods, numerical algorithms, global search, multimodal solutions, discrete problems, constrained models, and distributed processing among others. It also includes a number of difficult issues in synthesizing complex design processes and products such as multidisciplinary optimization, coordination processes, hierarchical methods, and agent networks.

Assessment

Mechanical engineering design in the United States is especially strong and has been in a global leadership role since the emergence of the field in the middle to late twentieth century. There is a strong U.S. representation in the VWC for this area, where an average of 79 percent of the 532 speakers are from universities, government agencies, and industries in the United States, with universities being the largest contingent.

Primary venues to publish design research contributions are the *Journal of Mechanical Design*, *Research in Engineering Design*, *Journal of Engineering Design*, *Design Studies, Computer-Aided Design*, and *Journal of Computing and Information Science in Engineering*. Many design-related articles are also published in operations research, numerical methods, and aerospace journals, along with publications closely related to specific engineering application fields such as manufacturing, product development, and process management. In 2005, U.S. authors contributed 29 percent of the articles and 34 percent of the 50 most-cited articles in the journal *Computer-Aided Design*. At the same time, there is an average U.S. contribution of about 30-40 percent of the journals listed above. The *Journal of Mechanical Design* has about 50 percent U.S. based authors, whereas the U.K.-based *Design Studies* has about 20 percent. Taken together, the VWC (>70 percent U.S.) and journal data (30-50 percent) indicate that the United States is the leader in computer-aided design research.

Dynamic Systems and Controls

The discipline of dynamic systems and control deals with the analysis and synthesis of control systems that typically include feedback loops. Feedback control systems involve system components such as a plant, a feedback controller, actuators, and sensors.

The control community is multidisciplinary, and active researchers come from aerospace engineering, electrical engineering, chemical engineering, mechanical engineering, and applied mathematics. For example, the American Control Conference, one of the most important conferences in the field, is sponsored by the American Automatic Control Council and membership societies including American Institute of Aeronautics and Astronautics, American Institute of Chemical Engineers, Association for Iron and Steel Technology, American Society for Civil Engineers, American Society of Mechanical Engineers, Institute of Electrical and Electronics Engineers, ISA-The Instrumentation, Systems, and Automation Society), and Society for Computer Simulation.

In the 1960s, major advances in the state of space control system design methodologies, including optimal control theory, were made in the United States and the Soviet Union. These advances resulted from the pursuit of space exploration, and the United States still remains the world leader in the subfield of control system design methodologies, particularly in optimal and robust control theories (see discussion in the assessment below).

For the purpose of the present study, the discipline is divided into the following subfields:

- **Modeling and Identification.** In the design of control systems, it is important to understand the dynamics of the controlled plant; therefore, the controlled plant is modeled and identified.
- **Control System Design Methodologies or Control Theories.** The feedback controller and other types of controllers must be designed to achieve various objectives such as stability, performance, robustness, and autoadaptive capability, and this is done with control system design methodologies and control theories.
- **Enabling Technologies (ET).** ET such as sensors or actuators and hardware components are important because the actual synthesis of control systems must be supported by them.
- **Mechatronics and Applications.** Motivations for research in the subfield of dynamic systems and control are often found in application domains, and application-oriented research has mechatronics aspects. Mechatronics refers to the synergistic integration of physical systems, decision-making, and electronic components such as digital signal processing (DSP) and intelligent sensors.
- **Robotics and Automation (R&A).** In the mechanical engineering community, there are a number of application domains such as vehicles, transportation, manufacturing, biomedical systems, modeling, and control at micro- or nanoscales and so on. R&A may be regarded as an application area, but its coverage and scope are broad.

Assessment

An average of 49 percent of the 714 speakers identified in the VWC were from the United States (appendix Table D-1), but the results for the subareas varied considerably. For example, about 60 percent of invited speakers in the subarea of control methodologies and control theories were from the United States, whereas there were 40 percent in mechatronics and applications.

The two leading journals in the field with strong methodology orientation are *Automatica* and *IEEE Transactions on Automatic Control*. In these journals, U.S. authors made up 23 and 36 percent of the authors represented in 2005, respectively. The difference in representation of U.S. experts as authors of publications in journals versus U.S. speakers at virtual congresses can be attributed to the broad scope of this discipline in terms of the number of researchers and the number of topics.

In other subareas, the dominance of the United States is not as evident, but the United States is certainly among the leaders. This is illustrated by the U.S. contribution to the most-cited articles in *IEEE Robotics and Automation*,[8] of 54, 46, 38, 34, and 48 percent respectively for the years 1995, 1997, 1999, 2001, and 2003. In the subarea of mechatronics and applications, 40 percent of virtual congress speakers are from the United States. This is consistent with the percentages of U.S. authors in application-oriented periodicals published in the United States: *IEEE Transactions on Control Systems Technology* (49 percent), and *IEEE-ASME Transactions on Mechatronics* (37 percent). U.S. authors, however, represent only 10 to 20 percent in *Control Engineering Practice* (*CEP*), another application-oriented periodical. This may be attributed to the preference of U.S. researchers to publish papers in ASME and IEEE journals, which are regarded as premier control journals in the international community; CEP is published by Elsevier in the Netherlands. In the *ASME Journal of Dynamic Systems, Measurement, and Control*, which covers the broad discipline of dynamic systems and control, 34 out of 81 articles (42 percent) were contributed by U.S. researchers.

Taken together, the VWC (49 percent U.S.) and journal results (30-50 percent U.S) indicate that the United States is among the world leader in dynamic systems and controls.

Energy Systems

Energy systems allow the conversion of an energy source (fossil fuel, nuclear plants, solar conversion) into a form that can be used immediately or stored and then recovered to fulfill a useful purpose (transportation, local power, etc.) The key issues and challenges in the subarea of energy systems presently center on reducing reliance on fossil fuels because of concerns regarding unstable supplies of petroleum, global climate change due to combustion product gases released into the atmosphere, and pollution resulting from fossil fuel production and conversion. With a few exceptions, federal research funding in this area has been very poor for some decades. The subareas that can be identified are (1) renewable energy systems and sources, (2) energy conversion and storage, and (3) nuclear energy.

- **Renewable energy systems and sources.** Include solar, wind, biomass, ocean thermal energy conversion (OTEC), and geothermal energy, and the systems used for converting energy from these sources into useful forms.
- **Energy conversion** (power plants, engines, fuel cells, photovoltaic, thermionic, etc.). Includes devices and systems for converting a primary energy source into a useful energy form.
- **Energy storage** (batteries, flywheels, phase change, etc.). Methods and systems for storing energy so that intermittent or steady energy production can be matched with intermittent or steady energy loads.
- **Nuclear energy** (modeling of reactor fuel and computational fluid dynamics for reactor design). Includes design, analysis, and testing of advanced nuclear power systems such as high-temperature gas cooled reactors, as well as modification and safety analysis of existing nuclear systems.

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[8] *IEEE Transactions on Robotics and Automation* split into two new titles in 2004: *IEEE Transactions on Robotics* and *IEEE Transactions on Automation Science & Engineering*.

Assessment

The VWC for the area of energy systems resulted in 68 percent of the 274 speakers being from the United States, which indicates a strong leadership position in this area. However, an examination of article authorship in seven journals (see appendix Table C-1) in this area showed the average U.S. contributions to be about 30 percent. U.S. contributions to the *Journal of Power Sources* are around 20 percent, while U.S. contributions to the most-cited articles in this journal average around 22 percent over the 1995-2005. The combined VWC representation (68 percent U.S.) and the journal article results (20-30 percent) indicates that the United States is among the leaders in energy systems with well-recognized researchers, and the lack of recent publications in this area shows a significant weakening of leadership.

Manufacturing and Computer-Aided Manufacturing

Manufacturing is the production of goods and services using raw materials and labor, Many of the specific issues associated with manufacturing are being done by mechanical engineers and include development of processes for creation of materials and material surfaces (textures) and interfaces, by machining and molding, for such varied uses as reducing drag of automobiles, creating the next generation of data storage devices, and developing concepts and tools (electrooptomechanical) for automated assembly.

For the purposes of this study, manufacturing was divided into five subareas: processes, tooling and equipment, systems, metrology, and quality.

- **Manufacturing Processes.** Involve materials removal processes (e.g., turning, milling, drilling, grinding), nonconventional materials processes (e.g., electrical discharge machining, electrochemical machining, energy beams such as laser, ion focus beam, or water jet), materials deformation processes (e.g., sheet forming, bulk forming, rolling, extrusion), casting processes, sinter and powder metallurgy (e.g., ceramic, powder metals), joining processes, and assembly processes
- **Manufacturing Toolings and Equipment.** Covers cutting tools, dies and molds, and fixtures, as well as computer numerical control and high-speed machines).
- **Manufacturing Systems.** Have to do with flexible manufacturing systems, reconfigurable manufacturing systems, group technologies, and process planning.
- **Manufacturing Metrology.** Involves coordinate measuring machines, optical gauges, and in-process inspection.
- **Manufacturing Quality.** Covers statistical process control (e.g., “6-Sigma”), variation reduction, and root cause identification)

Assessment

According to the VWC results, about 50 percent of the 389 speakers named were from the United States. This was consistent across all the manufacturing subareas. This leadership position is further supported by an analysis of journals in this area. In the *ASME Journal of*

Manufacturing Science and Engineering, U.S. contributions to the top 50 most-cited articles amounted to about 70 percent. In addition, four out of the five manufacturing journals analyzed showed greater than 50 percent U.S. contributions on average (Appendix Table C-2). Together, these results indicate that the United States is the leader in manufacturing basic research.

Mechanics of Engineering Materials

This field has a long history both inside and outside the United States. Research in the United States has maintained a strong leadership due to the ability of researchers to rapidly apply the concepts of mechanics to new and evolving problems. Current and future fields of intense interest include mechanics of materials at very small length scales, application to complex hierarchical biological materials, and multiscale modeling and experimentation. Such foci permeate traditional fields such as damage mechanics and experimental mechanics by providing important new applications for mechanics and new tools by which to further our understanding of materials and enable the creation of devices and materials for the well-being of society.

- **Nanomechanics and nanomaterials.** Involves understanding at the nanometer level the mechanisms and limits of mechanical changes, the stability of materials, and the transfer of energy to and from materials.
- **Durability mechanics.** Has to do with the material science of large physical structures, largely involving fracture mechanics and the deterioration of materials.
- **Computational materials.** Involves numerical methods for the analysis of the nonlinear continuum response of materials, which includes: elasticity, inelasticity, molecular statics and dynamics modeling across atomistic, molecular, and continuum scales.
- **Experimental mechanics.** Has to do with understanding the mechanical behavior of materials, structures, and systems, especially at small scales and bridging between scales and bridging to theory.
- **Multiscale mechanics**: involves the use of theory, experiment, and numerical simulation in combination, to understand heterogeneous materials, biomaterials, composites, and micromechanics at all levels of function.

Assessment

The VWC results for mechanics of engineering materials show that U.S. organizers picked more than 70 percent U.S. speakers, while international researchers named 50 percent U.S. speaker's to participate.

U.S. researchers in the mechanics of engineering materials publish in a widerange of journals, some focused on the area of mechanics, such as the premier mechanics journal, *Journal of Mechanics and Physics of Solids* (*JMPS*), and with significant presence in journals specific to fields of application, such as *Journal of Biomedical Materials Research*. In *JMPS*, U.S. authors publish an average of about 65 percent of the most-cited articles. In addition, researchers have begun to broaden the visibility of the field and its contributions with publications in top general science journals such as *Science*, *Nature*, and *Nature Materials*. Overall, U.S. authorship is at about 50 percent for all articles combined in relevant journals. Together, these results indicate that the United States is the leader in the mechanics of engineering materials research.

Microelectromechanical Systems and Nanoelectromechanical Systems

Microelectromechanical systems (MEMS) is the technology of very small devices and systems having important dimensions at the micrometer level (i.e., between a micrometer and a millimeter), too small to machine with traditional physical methods but too large to build with chemical syntheses. Born from the semiconductor integrated circuit (IC) fabrication processes, MEMS technologies typically use deposition and etching of materials along with photolithographically defined mask patterns. Today, the fabrication arsenal has been enriched by several IC processes commercialized specifically for MEMS (e.g., deep reactive ion etching) and many non-IC processes modified for microfabrication (e.g., microelectrodischarge machining, electroplating into micromolds). MEMS is considered coming of age with a few commercial successes of high visibility (e.g., automobile airbag sensor, micromirror array for high-definition display, inkjet printhead). Although the success is most often viewed through applications, the fabrication technologies constitute the indispensable basis for the next wave of success across fields beyond electronics (e.g., biomedical). With the focus of funding shifted to application research years ago however, MEMS appears to have lost support in fundamental and core research rather prematurely. Despite dramatic miniaturization, MEMS is still within the realm of continuum mechanics.

Nanotechnology (Nano) is poorly defined today, but it generally deals with engineering at the nanometer scale. Originally inspired by molecular engineering in its core intent (i.e., building three-dimensional structures molecule-by-molecule in bottom-up approaches), nanotechnology is currently dominated by material syntheses, thinfilms, and nanoscale ICs.

To assess the current status of the U.S. contribution to MEMS/Nano, the following representative subareas were examined:

- **Fundamental Issues in MEMS and Nano.** The physics unique to the scale are the main points of focus for the field. As an example for both MEMS and Nano, the surface-to-volume ratio is extremely large compared to conventional mechanical engineering devices and systems. The scale effects are prohibitive in some cases but enabling in others. Understanding the fundamentals allows one to avoid the problems and take advantages of the unique opportunities of being in the given scale.
- **Design and Modeling.** Design and Modeling are based on the fundamental issues and allow one to design products and predict their performance, minimizing the trial-and-error development cycles. Modeling in MEMS typically requires simultaneous solution of multiphysics issues. Modeling for Nano often requires simulation at the molecular level, and the boundaries may be blurred between mechanical engineering and chemistry even for machines in nanometer scale.
- **Micro/Nano Process Technologies.** The ability to fabricate objects in micro- or nanometer scale is a major obstacle. MEMS processes typically use top-down methods, forming the shape by removing unnecessary portions. Nano processes are said to be based on bottom-up methods, building by placing the minimum unit of materials one at a time. However, most

nanofabrication methods today are extensions of known methods (e.g., embossing into molds having submicrometer features).

- **Micro/Nano Devices and Systems.** The components or final products whose key functions originate from micro- or nanoscale features are Micro/Nano devices and systems. For example, an airbag deployment sensor is a complete microdevice or system, which in turn is a component of an automobile. The same can be said for a digital light processor (DLP) for high-definition television (HDTV) or the printhead of an inkjet printer. On the contrary, examples of devices are rare as yet in the Nano field.

Assessment

For the VWC, 57 percent of the 83 speakers were from the United States (non-U.S. speakers were largely from Japan and the Netherlands), indicating U.S. leadership in this area.

MEMS researchers publish in the *Journal of Microelectromechanical Systems* (IEEE-ASME, U.S.), *Journal Micromechanics and Microengineering* (Institute of Physics, U.K.), *Sensors and Actuators* (Elsevier, the Netherlands), and *Lab on a Chip* (Royal Society of Chemistry, U.K.), among others. Nano researchers publish in a much wider range of journals, most notably in *Nano Letters* (American Chemical Society, U.S.). However, more Nano-related articles are published in many other established journals in chemistry and material science journals.

Based on journal analysis of the 50 most cited articles, U.S. authors represent 70 percent and 20 percent of the authors respectively in the *Journal Microelectromechanical Systems* and the *Journal of Micromechanics and Microengineering*. At the same time, in 2005, the U.S. contribution was about 70 percent of the 146 articles published in the *Journal Microelectromechanical Systems* and about 30 percent of the 353 articles in the *Journal Of Micromechanics and Microengineering*.

Based on the combined results of the VWC (>50 percent U.S.) and journal analysis (30-50 percent U.S.), the United States is among the leaders in the world in both MEMS/Nano research.

Thermal Systems and Heat Transfer

Research and development in thermal systems and heat transfer span a variety of fields including fluid mechanics (e.g., multiphase flows, plasmas, turbulence, biofluids), heat transfer (e.g., convection, conduction, radiation, phase change), and micro- and nanothermofluid systems and applications. Applications and technology development have been led by U.S. researchers include aerospace, nuclear, propulsion, electronics and photonics thermal management, advanced manufacturing, laser-material interactions, HVAC (heating, ventilation, and air conditioning), and flow control.

- **Combustion.** Involves experimental and analytical studies in combustion, applications in power generation, propulsion, and fire safety.
- **Heat transfer.** Has to do with studies of fundamental heat transfer phenomena in radiation, conduction, convection, mixed modes, and phase change.

- **Fluid mechanics.** Includes plasmas, multiphase flow, turbulence, biofluids, supersonic and hypersonic flows, and shocks.
- **Nano/Micro systems.** Involve thermal properties and heat transfer in fluids, nanofluidics, and nanocomposites; and near-field effects in radiation, phonon and photon transfer, and property modifications at a small scale.
- **Applications.** Are very wide ranging, including electronic cooling, aerospace, nuclear, propulsion, advanced manufacturing, laser-material interactions, HVAC, flow control, power generation, and electronics cooling.

Assessment

The VWC results for the area of thermal systems and heat transfer show that an average of 65 percent of the 562 speakers were from the United States. This is similar to the U.S. contribution to the *ASME Journal of Heat Transfer*. An average of 50 percent of the 50 most-cited articles for the *ASME Journal of Fluids Engineering* were U.S. authored. In 2005, an average of 40 percent of 10 selected journal articles in this area were U.S. authored (see appendix Table C-2). Based on the combined results of the VWC (65 percent U.S.) and journal analysis (30-50 percent U.S.), the United States is the world leader in thermal systems research.

Tribology

Tribology is the study of surfaces in relative motion. It encompasses the areas of friction, lubrication, and wear. Tribology is an enabling technology in that all mechanical systems involve surfaces in relative motion that require control of friction, motion, and wear. Mechanical systems could not operate without triboelements. New mechanical systems, or upgrades of existing mechanical systems, often require new developments in tribology to accommodate increases in speed, load, or operating temperature. Research in tribology tends to be done in the mechanical engineering community, although considerable contributions also come from the physics, chemistry, material science, and applied mathematics communities.

The term *tribology* originated in Great Britain in 1966, and the British, along with Americans, tend to dominate the field. Other countries making significant contributions tribology include France, Japan, Germany, and to a lesser extent Israel, Norway, Finland, Sweden, The Netherlands, Switzerland, and China. Prior to the collapse of the Soviet Union there were considerable contributions from that country. The continuous driver in tribology research is to push mechanical systems to higher loads, higher temperatures, higher speeds, and longer more reliable life.

Tribology can be divided into five subareas.

- **Hydrodynamic phenomena.** Are concerned with those situations in which the surfaces are separated by a fluid, either a liquid or a gas, and a pressure in the fluid is generated by the relative motion of the surfaces, or an external source, sufficient to support the load on the surfaces and keep the surfaces from contacting one another.

- **Friction and wear.** Is concerned with solid surfaces in relative motion and in contact with one another resulting in friction forces resisting motion and resulting in the wear of surfaces.
- **Tribomaterials.** Involves all types of material development and selection for tribological elements such as bearings, brakes, cams, and tires, and the lubricants used in triboelements.
- **Contact mechanics and surface engineering.** Has to do with surface and near surface material deformation and fatigue resulting from highly concentrated loads occurring in some triboelements, such as rolling element bearings and rail-wheel contact.
- **Diagnostics.** Involves developing techniques for early detection of mechanical failure in machinery.

Assessment

An average of about 50 percent of the 471 VWC speakers in the area of tribology were from the United States. The other countries with large contributions of speakers include the United Kingdom, France, and Germany in that order. There are also significant numbers from Japan, the Netherlands, Finland, Italy, and Sweden. The United Kingdom is strong in all subsubfields, while France is strong in hydrodynamic phenomena and Germany is strong in the area of tribomaterials.

Primary venues to publish tribology research contributions are the *ASME Journal of Tribology*, the Society of Tribologists and Lubrication Engineers' *STLE Tribology Transactions*, *Wear*, *Tribology International*, and *Tribology Letters*. Many tribology-related articles are also published in physics, chemistry, and material science journals, as well as publications closely related to specific engineering applications fields such as transportation, environmental control, and manufacturing. Of the 50 most-cited articles in the journal *Wear,* an average of about 20 percent were by U.S. authors. U.S. authors appear more frequently among the most-cited authors than among authors in general in that publication. The reason U.S. authors appear less frequently in *Wear* than among the VWC authors may be that U.S. authors are more likely to publish in the two major U.S. publications in tribology—ASME *Journal of Tribology* and *STLE Tribology Transactions*. *Wear* is published in Europe.

At the same time, about 30-50 percent of authors in the U.S.-based tribology journals mentioned above are from the United States, while in the British based journals, about 20 percent of the authors are from the United States. *Tribology Letters* has about 40 percent U.S. based authors.

Based on the combined results of the VWC (50 percent U.S.) and journal analysis (20-50 percent U.S.), the United States is among the world leaders in tribology.

SUMMARY

Mechanical engineering is the foundation for the creation of the industrialized world, and it is a central element of all engineering disciplines. It is at the heart of design, creation, and manufacturing of wealth-generating devices in the twenty-first century. Research in mechanical engineering is no doubt essential to future technological innovation. Evidence for current basic research leadership in mechanical engineering comes from an analysis of journal articles, most-cited articles, and virtual congresses conducted by the panel. Overall, the United States is certainly among the leaders in mechanical engineering basic research. However, excellent mechanical engineers throughout the world provide stiff competition for the United States.

- In 2002-2006, the United States published 24 percent of the mechanical engineering articles in the world. For 1987-1991, the U.S. contribution was 48 percent.
- U.S. mechanical engineers contribute strongly as authors to the leading research journals in this field, accounting for about 40 percent of the articles and 40 percent of the most-cited articles in the 68 selected journals.
- U.S. mechanical engineers contributed 65 or more out of the 100 most-cited articles in the Scopus database for the timeframe 1987 to 2006.
- The combined virtual congress and journal analysis supports that the United States is the leader or among the leaders in all areas of mechanical engineering basic research (Table 2-5).

TABLE 2-5 Assessment of Mechanical Engineering Basic Research Leadership for Designated Areas of Mechanical Engineering, Based on Combined Results of the Virtual World Congress and Most-cited Articles

Assessment	Area	VWC (% U.S.)	Most-cited articles (%U.S.)*
The leader	Bioengineering	75	20-40
	Design	79	30-50
	Manufacturing	53	50-70
	Mechanics of Engineering Materials	76	50-65
	Thermal Systems & Heat Transfer	65	30-50
Among the leaders	Acoustics & Dynamics	53	30-50
	Computational Mechanics	49	30-50
	Dynamic Systems & Controls	49	30-50
	Energy Systems	66	30
	MEMS / NEMS	57	30-50
	Tribology	48	20-50

*The range given is based on U.S. percent contributions across all journals analyzed for each area of mechanical engineering basic research.

Overall, the United States is among the leaders in mechanical engineering research, with the following average contributions:

- 50 percent of VWC speakers,
- 40 percent of journal articles, and
- 40 percent of most-cited articles.

3

Key Factors Influencing U.S. Leadership in Mechanical Engineering Basic Research

In the previous chapter, the panel evaluates leadership in mechanical engineering as measured by numbers and quality of journal articles and a virtual congress conducted by the panel members. This leadership is influenced by a multitude of factors that are largely the result of national policy, economics, and available resources of each country in the world. Here, the panel focuses on three key factors that influence the international leadership status of U.S. mechanical engineering basic research:

1. **Centers, facilities, and instrumentation:** the physical infrastructure for conducting mechanical engineering basic research
2. **Human resources:** the national capacity for producing and employing mechanical engineering students and degree holders.
3. **Research and development funding:** financial support for conducting mechanical engineering research

CENTERS, FACILITIES, AND INSTRUMENTATION

Modern science and engineering research involves interdisciplinary collaboration, requiring specialized hardware and software often used by multiple disciplines. At the same time, mechanical engineers have specific needs to be met. The health and competitiveness of mechanical engineering research depends on the availability of cutting-edge facilities at U.S. universities and national laboratories. Examples of such facilities are described below. When available, important international facilities are also included. This section does not provide an analysis of the availability of or funding for centers, facilities, and instrumentation— it is meant to highlight the types of such infrastructure resources that are important for carrying out mechanical engineering research.

The types of centers, facilities, and instrumentation of interest to mechanical engineering research fall into the following broad categories:

- Materials characterization and micro- or nanofabrication

- Manufacturing, automation, and rapidprototyping
- Biomechanical engineering
- Cyberinfrastructure
- Energy and flow systems

Materials Characterization and Micro- or Nanofabrication

In the mechanics of engineering materials subarea, central facilities are extremely important, especially for the experimental side of the research. As the frontiers of research have moved to an increasingly small scale, access to electron microscopy, scanning probe microscopy and other specialized equipment is essential. These types of equipment are typically not found in individual research labs, they are housed in central facilities on campuses or in other research centers. At the elite research universities in the United States, access to such equipment is quite good, though in some cases usage fees can be excessive. Internationally, the same situation holds, where one potential difference is that in many foreign nations equipment is staffed by trained technicians who can facilitate the consistent quality as well as the speed of work. In addition to this equipment, access to large-scale, unique equipment such as synchrotrons is increasingly important. In the United States these facilities are run by the U.S. government and access for academic work is well supported.

Characterization of materials often requires high-energy light sources—such as synchrotron and neutron sources—or other specialized facilities that need a significant level of funding to operate and maintain. These are typically available only at national facilities both here and abroad.

Examples of important synchrotron sources include the following: [1] Advanced Light Source (ALS), Advanced Photon Source (APS), National Synchrotron Light Source (NSLS), Stanford Synchrotron Radiation Laboratory (SSRL), Los Alamos Neutron Scattering Center, IPNS (Intense Pulsed Neutron Source) at Argonne and High Flux Isotope Reactor at Oak Ridge National Laboratory in the United States; Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY) in Germany; European Synchrotron Radiation Facility (ESRF) in France; INDUS 1/INDUS 2 in India; and National Synchrotron Radiation Research Center (NSRRC) in Taiwan.

Examples of important neutron sources include[2] Spallation Neutron Source, Oak Ridge National Laboratory and the University of Missouri Research Reactor Center in the United States; ISIS-Rutherford-Appleton Laboratories in the United Kingdom; and Hi-Flux Advanced Neutron Application Reactor in Korea.

Most research-intensive universities are well equipped with conventional micro- and nanofabrication techniques such as thin-film deposition (e.g. chemical vapor deposition, physical vapor deposition), lithography, chemical etching, and electrodeposition, as well as characterization techniques such as electron microscopy, electron and X-ray diffraction, and probe microscopy that are used routinely to characterize small structures, small volumes, and thin films. However, the ability to characterize extremely small nanostructures or to tailor materials at an atomic level requires much more specialized equipment. The Department of

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[1] For a full list of worldwide synchrotron light sources, see *http://www.lightsources.org/cms/?pid=1000098*.

[2] For a full list of worldwide neutron sources, see the National Institute of Standards and Technology Center for Neutron Research at *http://www.ncnr.nist.gov/nsources.html*.

Energy is now in the process of opening five Nanoscale Science Research Centers[3] that will provide just such capabilities. Four of these centers are listed here, and one is mentioned later in the discussion of biological capabilities.

1. *The Center for Nanoscale Materials* is focused on fabricating and exploring novel nanoscale materials and, ultimately, employing unique synthesis and characterization methods to control and tailor nanoscale phenomena.
2. *The Center for Functional Nanomaterials* provides state-of-the-art capabilities for the fabrication and study of nanoscale materials, with an emphasis on atomic-level tailoring to achieve desired properties and functions.
3. *The Center for Integrated Nanotechnologies* features low vibration for sensitive characterization, chemical and biological synthesis labs, and clean rooms for device integration.
4. *The Center for Nanophase Materials Sciences* is a collaborative nanoscience user research facility for the synthesis, characterization, theory-modeling-simulation, and design of nanoscale materials.

Other agencies and even some universities support key nanofabrication facilities. The National Science Foundation funds several nanofabrication facilities (e.g., at Cornell University) that are available to external users and are part of a larger National Nanotechnology Infrastructure Network (NNIN). [4] The Cornell Nanofabrication Facility[5] provides fabrication, synthesis, characterization, and integration capabilities to build structures, devices, and systems from atomic to complex large scales. Carnegie Mellon University independently operates its own user facility that serves the broader community. The Nanofabrication Facility at Carnegie Mellon[6] provides facilities for data storage, thin film, and device development and includes extensive cleanroom space.

Manufacturing, Automation, Rapidprototyping

Mechanical engineers are involved in all aspects of manufacturing from product design to process controls. A key infrastructure resource for manufacturing is the Manufacturing Engineering Laboratory (MEL) at the National Institute of Standards and Technology (NIST). MEL conducts research and development, provides services, and participates in standards activities related to mechanical and dimensional metrology. One particular area of success has been in lean manufacturing; many industrial success stories are available on the NIST Manufacturing Extension Partnership website.[7] Similar facilities exist at universities, such as the NSF Center for Reconfigurable Machining Systems (RMS) at the University of Michigan, Ann

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[3] *http://www.science.doe.gov/Sub/Newsroom/News_Releases/DOE-SC/2006/nano/index.htm.*
[4] *http://www.nnin.org.*
[5] *http://www.cnf.cornell.edu.*
[6] *http://www.nanofab.ece.cmu.edu.*
[7] *https://www.mepcenters.nist.gov/cims2-web/pub/ss.mep?sfc=1&state=list* (accessed September 26, 2007).

Arbor. "[RMS) is one designed at the outset for rapid change to quickly adjust its production capacity and functionality in response to sudden market changes and customer demand."[8]

Mechanical engineers are concerned with the calibration and quality control of measurement of instruments and manufacturing devices. Microcomputed tomography (microCT) is used for high resolution imaging. Another example is the use of micropatterning (Columbia University has three N.Y. state-funded centers for conducting this kind of research). NIST offers extensive measurement and standardization facilities.

In the area of automation and dynamic systems and controls, many university centers provide important shared facilities, such as the Iowa Driving Simulator at Iowa State University or automated highway research facilities at the University of California at Berkeley.

Physical prototyping infrastructure facilities allow researchers to rapidly produce prototypes of products as a means to better validate theoretical and applied developments. Although a small handful of rapid prototyping centers exist across the nation (e.g., Milwaukee School of Engineering, Georgia Tech, University of Louisville) and isolated prototyping machines at a large number of universities, there is very limited accessible infrastructure dedicated to providing researchers the ability to test and validate their advancements in design. Emerging quickly, largely because of digital advances and global market pressures, is the need for virtual prototyping, allowing researchers to create functional digital models of products and systems while also providing tactile feedback using haptic and virtual reality technologies. Although there are a small handful of design centers with virtual prototyping capabilities (e.g., Iowa State University, University of Iowa, University at Buffalo-State University of New York), and isolated researchers with haptic devices and visualization facilities, there is limited infrastructure dedicated to providing researchers the ability to virtually test and validate their advances in design research.

In addition, more action is being taken to coordinate R&D in manufacturing across federal agencies, including joint solicitations through the efforts of the Interagency Working Group (IWG) on Manufacturing Research and Development.[9] One report that will be forthcoming from the IWG is related to manufacturing R&D in three specific areas: (1) nanomanufacturing; (2) manufacturing for the hydrogen economy; and (3) integrated and intelligent manufacturing systems.

Biomechanical Engineering

The need for biomechanical engineering facilities fall into three areas: (1) characterizing signal transduction (cells sensing external signals) such as effects of shear force, which requires multiscale computational power; (2) imaging at smallest length scales (i.e., nanometer) level; and (3) mimicking biological tissues—biomimetics (e.g., tissue engineering). Two examples of new centers providing state-of-the-art facilities and approaches for bioengineering research are given below—starting with one of the DOE's nanoscale science research centers.

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[8] *http://www.erc-assoc.org/factsheets/l/html/erc_l.htm* (accessed September 24, 2007).

[9] *http://www.ostp.gov/mfgiwg/* (accessed September 26, 2007).

1. *The Molecular Foundry* provides instruments and techniques for users pursuing integration of biological components into functional nanoscale materials. [10]
2. *The Institute for Systems Biology* takes a multidisciplinary approach to addressing systems biology that includes integration of research in many sciences including biology, chemistry, physics, computation, mathematics, and medicine. [11]

Cyberinfrastructure

According to the National Science Foundation, cyberinfrastructure refers to the distributed computer, information, and communication technologies combined with the personnel and integrating components that provide a long-term platform to empower the modern scientific research endeavor.[12] Advances in computational mechanics depend heavily on (1) advances in high-performance computing (HPC) devices; (2) new software that is compatible with the changing computer platforms; and (3) new algorithms and methods to model advanced problems in mechanical engineering, such as multiscale and multiphysics events in nanomanufacturing.

Two examples of engineering cyberinfrastructure capabilities are the following:

1. *The Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER)* addresses large-scale human-stressed aquatic systems through collaborative modeling and knowledge networks. [13]
2. *The Network for Computational Nanotechnology* connects theory, experiment, and computation in a way that makes a difference to the future of nanotechnology. [14]

Energy and Flow Systems

Generally, research in thermal systems and heat transfer relies on small-scale lab experiments. The exception is large flow systems such as wind tunnels and facilities for testing turbine blade cooling systems, nuclear fuel assembly thermal test systems, and other specialized facilities. Large scale wind tunnels for sub-, super-, and hypersonic flow were originally maintained by the National Aeronautics and Space Administration (NASA) under its aeronautics program. This program has been cut back significantly, and many of these facilities have been put in storage or permanently dismantled. Wind tunnels are also used for acoustics and dynamics research. NASA has one at Langley-used for high-noise chambers. Slow-neutron sources (such as the Savannah River Site reactor) are used for real-time imaging of casting and engines.

Turbines are also critical to energy and research in aeropropulsion and turbomachinery, and laboratories or facilities exist mainly at universities—for example the gas turbine laboratory (GTL) at the Massachusetts Institute of Technology, Ohio State University, or Georgia Institute

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[10] *http://foundry.lbl.gov/*

[11] *http://www.systemsbiology.org/*

[12] See extensive list of links on cyber-infrastructure at *http://www.nsf.gov/crssprgm/ci-team/#ecl.*

[13] *http://cleaner.ncsa.uiuc.edu/home/.*

[14] *http://www.ncn.purdue.edu/.*

of Technology. There is also a well-known GTL at the National Research Council Canada (NRC) Institute for Aerospace Research, located in Ottawa.

HUMAN RESOURCES

Human resources are an essential component of leadership in mechanical engineering. Below, the panel discusses overall characteristics of worldwide science and engineering human resources, and then focuses on some important features of the U.S. supply of mechanical engineers.

Strong Competition for International S&E Human Resources

In terms of sheer numbers of engineering undergraduate degrees granted, the United States is outpaced by China, Japan, Russia, and South Korea (Table 3-1). In the physical and biological sciences, the United States is behind India, China, and Russia. Moreover, the United States ranks lower than most industrialized nations in the percentage of 24-year-olds who hold their first university degrees (e.g., bachelor's degree in the United States) in natural sciences and engineering (NS&E: see Figure 3-1). U.S. competitors in Europe and Asia are producing a higher percentage of NS&E degree holders.

TABLE 3-1 Countries with the Greatest Numbers of First University Degrees in Engineering Compared with Degrees in Physical and Biological Sciences

	Engineering	Physical and Biological Sciences
China (2003)	351,537	103,409
Japan (2004)	98,431	19,727
Russia (1999)	82,409	101,320
South Korea (2002)	64,942	12,864
United States (2002)	60,639	79,768
Mexico	44,682	7,695
Taiwan	41,947	4,294
India (1990)	29,000	147,036
Italy	26,747	9,193
France (2002)	26,414	27,750

SOURCE: National Science Foundation, *Science and Engineering Indicators 2006*, Appendix Table 2-37.

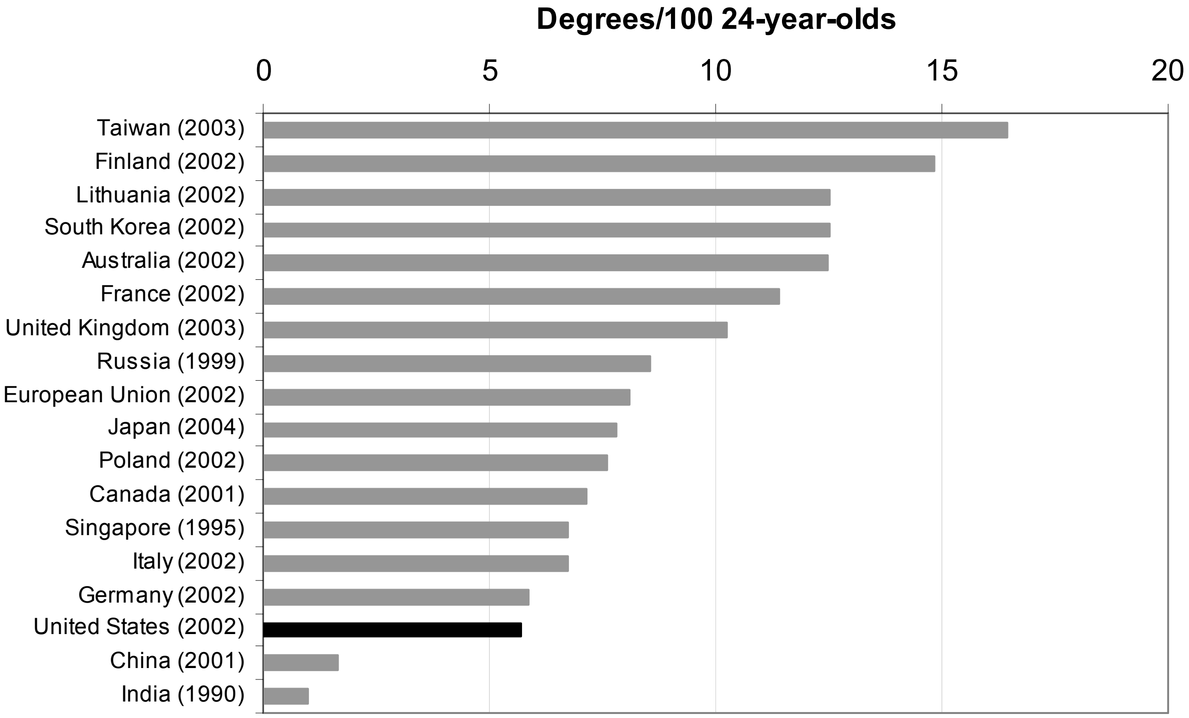

FIGURE 3-1 Ratio of first university natural science and engineering degrees per 100 24-year-olds by country. NS&E includes physical, biological, agricultural, and computer sciences; mathematics; and engineering.
SOURCE: National Science Foundation, *Science and Engineering Indicators 2006* , appendix table 2-37, based on data from Organization for Economic Cooperation and Development, Center for Education Research and Innovation, Education database, *www1.oecd.org/scripts/cde/members/edu_uoeauthenticate.asp*; United Nations Educational, Scientific, and Cultural Organization, Institute for Statistics database, *http://www.unesco.org/statistics, and national sources.*

The United States is the single largest producer of natural science and engineering doctoral degrees (see Figure 3-2). However, the number of U.S. doctorates has been declining gradually since the late 1990s. At the same time, the number of China’s doctorates leveled off after rapid growth in the early 1990s.

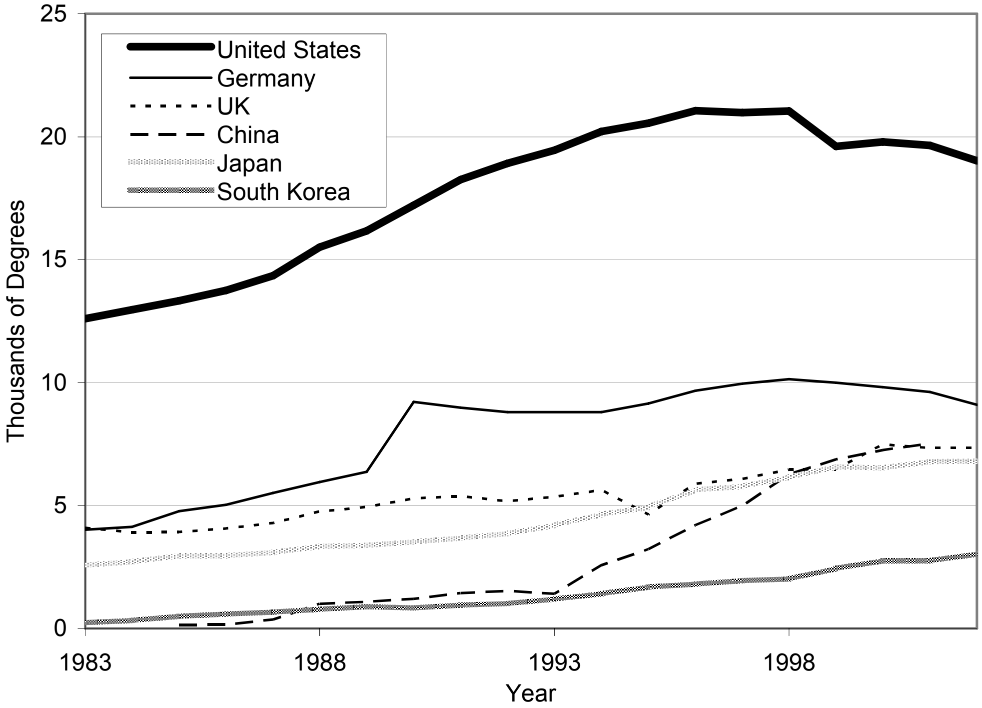

FIGURE 3-2 Natural science and engineering doctoral degrees, 1983-2002.
SOURCE: National Science Foundation, *Science and Engineering Indicators 2006*, Figure 2-34.

The United States also has increasingly relied on foreign-born scientists and engineers. In 2000, 38 percent of U.S. Ph.D.s granted were to foreignborn scientists and engineers, whereas in 1990 only 22 percent were foreignborn. A large portion of those who come to the United States to earn a Ph.D. in science or engineering, stay here. A 2005 study found that 71 percent of foreign citizens who received S&E doctorates from U.S. universities in 2001 lived in the United States in 2003.[15] The study also found that among S&E disciplines, the highest stay rates were for computer and electrical and electronic engineering and the physical sciences. Most foreign doctorate recipients come from four countries. The stay rates for two of these countries, China (90 percent) and India (86 percent), are very high, while those for the other two, Taiwan (47 percent) and Korea (34 percent), are well below the average for all countries.

Steady Supply of Mechanical Engineers in the United States

A good measure of the near-term supply of new mechanical engineers is to look at the recent trend in the number of graduate students in the United States, which is discussed in more detail below. A measure of the midterm availability of U.S. research mechanical engineers is provided by the number of B.S. mechanical engineering degrees granted in the United States

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[15] M.G. Finn, 2005, *Stay Rates of Foreign Doctorate Recipients from U.S. Universities, 2003,* Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee.

(Figure 3-3); which has drifted down by about 6 percent over the most recent decade for which data are available—from 15,297 in 1994 to 14,368 in 2004.[16]

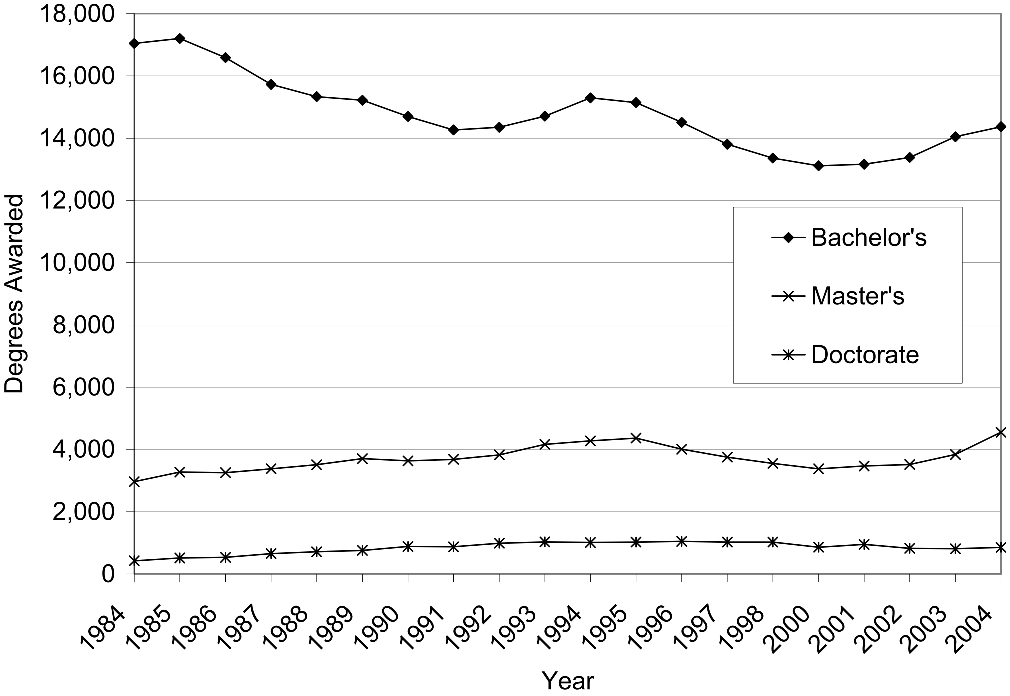

FIGURE 3-3 Mechanical engineering degrees awarded, by degree level: 1984–2004. SOURCE: National Science Foundation, Division of Science Resources Statistics. 2006. *Science and Engineering Degrees: 1966–2004*. January 2007. Arlington, VA.

On a still longer time scale, the supply of scientists and engineers overall depends on the current state of the U.S. K-12 educational system. Here, there have been ongoing concerns about K-12 math and science education in the United States compared with other countries, based largely on the results of internationally administered tests. In 2004, the NSF summarized the situation: "U.S. students are performing at or below the levels attained by students in other countries in the developed world," and "In international comparisons, U.S. student performances become increasingly weaker at higher grade levels."[17] More recent results reported by NSF showed a more mixed picture—where U.S. fourth and eighth grade students scored above average on the international tests, but U.S. 15-year-olds scored below average.[18]

Because of the difficulties in locating quantitative data on mechanical engineering human resources at the international level, the panel concentrated on the trends in the number of U.S. mechanical engineering graduate students and Ph.D.s. The data shown in the following figures demonstrate that the numbers of U.S. graduate students and Ph.D.s have remained fairly steady

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[16] National Science Foundation, Division of Science Resources Statistics, 2006, *Science and Engineering Degrees: 1966-2004,* Arlington, Virginia.
[17] National Science Foundation, 2004, *Science and Engineering Indicators 2004*, Arlington, Virginia.
[18] National Science Foundation, 2007 *Science and Engineering Indicators 2006*, Arlington, Virginia.

over the past 10-20 years due to the growing number of foreign-born mechanical engineering graduate students and Ph.D.s.

Between 1985 and 2005 (Figure 3-4), there was a fluctuating, but overall steady, supply of graduate students enrolling in mechanical engineering. In the late 1990s, there was a decline in the number of U.S. citizens and permanent residents enrolling in mechanical engineering graduate programs that has begun to rebound more recently. Increasing enrollment of temporary residents has compensated for the declines in U.S. citizens and permanent residents.

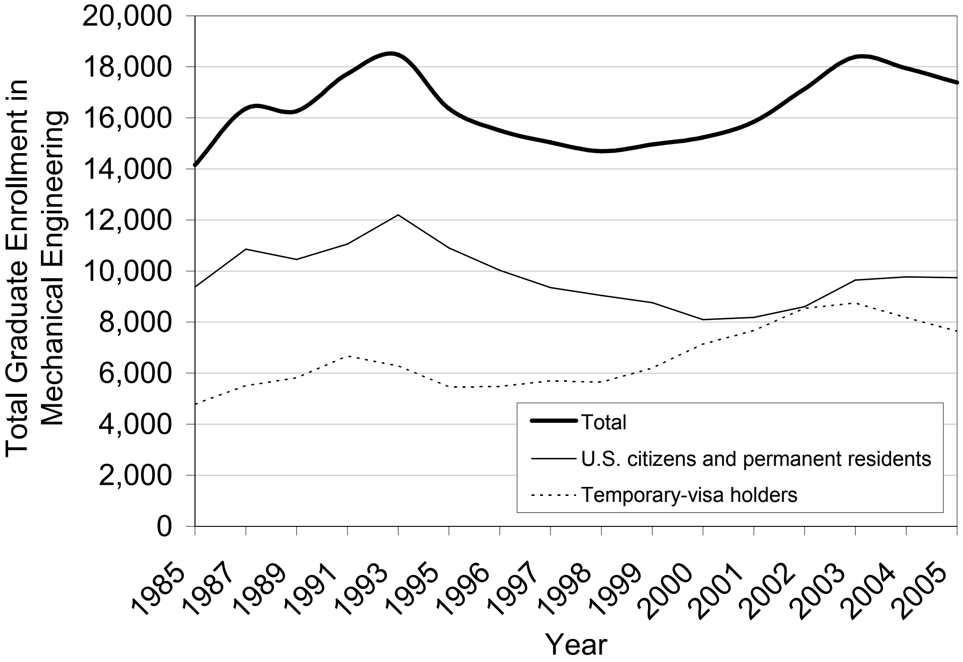

FIGURE 3-4 Total graduate enrollment in mechanical engineering and enrollment based on residency status: U.S. citizen or permanent resident versus temporary residents, 1985-2005. SOURCE: National Science Foundation, Division of Science Resources Statistics (NSF/SRS), *Survey of Graduate Students and Postdoctorates in Science and Engineering*, Integrated Science and Engineering Resources Data System (WebCASPAR), *http://webcaspar.nsf.gov*.

A better indicator of current trends, however, is to look at first-time full-time graduate enrollments, because overall graduate student enrollments include individuals who began school up to five or six years ago. Again during the period shown, first-time full-time graduate student enrollments in the United States fluctuated but overall remained above 2,800 (Figure 3-5).

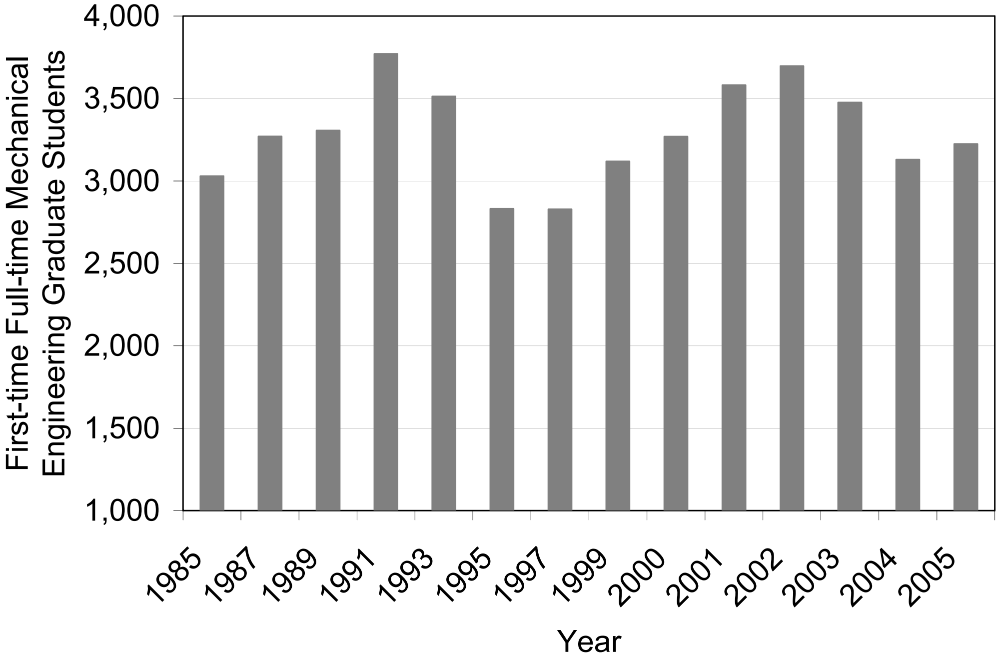

FIGURE 3-5 First-time full-time mechanical engineering graduate students: Selected years, 1985-2005.
SOURCE: NSF/SRS, *Survey of Earned Doctorates*, Integrated Science and Engineering Resources Data System (WebCASPAR), *http://webcaspar.nsf.gov*.

There has been concern about the potential impacts of immigration policies following the terrorism events on September 11, 2001. A breakdown of first-time full-time enrollments by residency (Figure 3-6) shows that for 2003-2005, temporary resident enrollments fell below those of U.S. citizens and permanent residents.

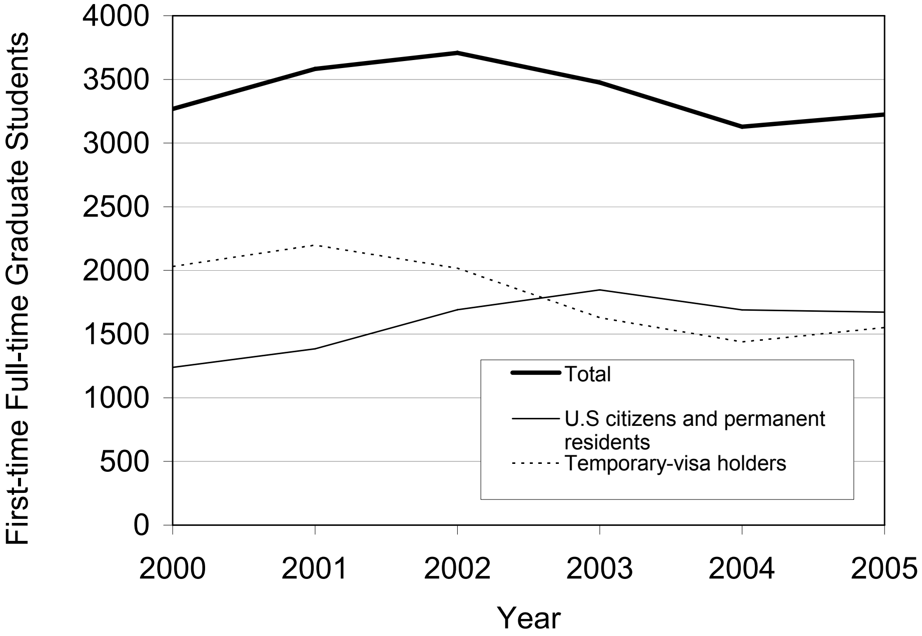

FIGURE 3-6 First-time full-time mechanical engineering graduate student enrollment by citizenship and residency status.
SOURCE: NSF/SRS, *Survey of Earned Doctorates*, Integrated Science and Engineering Resources Data System (WebCASPAR), *http://webcaspar.nsf.gov* (accessed July 11, 2007).

The competitiveness of mechanical engineering research is dependent on the number of mechanical engineering Ph.D.s granted. As shown in Figure 3-7, between 1975 and 1995, the number of earned mechanical engineering Ph.D.s in the United States more than doubled due to increases in the number of doctorates awarded to both U.S. citizens and temporary residents. Over the past 10 years for which data are available (1995-2005), the number of earned mechanical engineering doctorates awarded each year has fluctuated, but overall remained above 800 doctorates awarded per year. At the same time, there was a significant decline in the number of doctorates awarded to U.S. citizens.

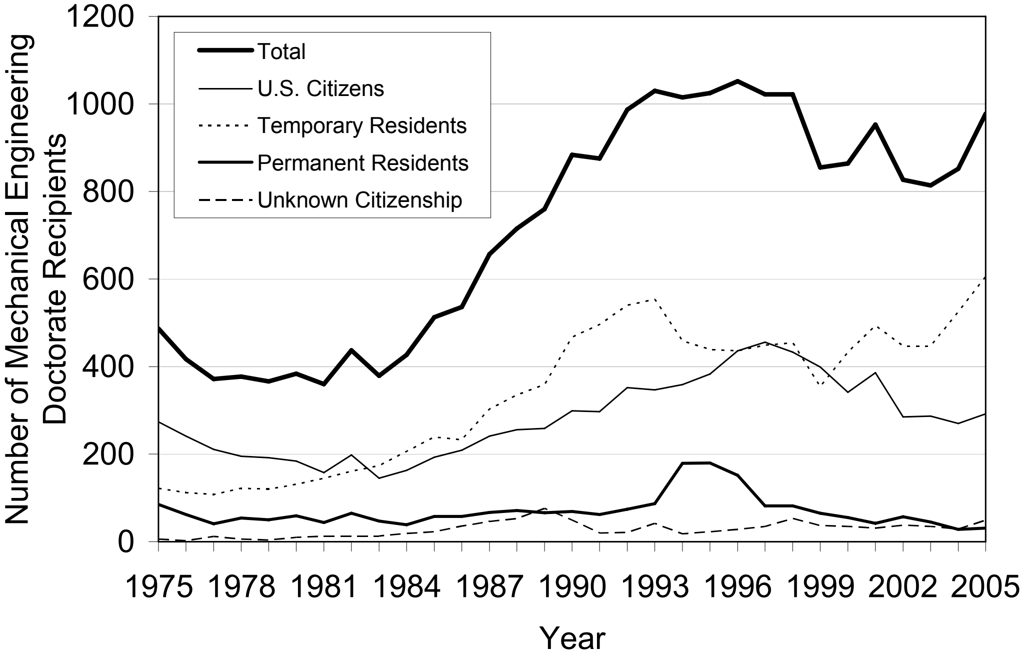

FIGURE 3-7 Earned doctoral degrees in mechanical engineering from U.S. institutions as a function of residency status for 1975-2005.
SOURCE: NSF/SRS, *Survey of Earned Doctorates*, Integrated Science and Engineering Resources Data System (WebCASPAR), *http://webcaspar.nsf.gov* (accessed September 5, 2006).

Graduate student support also has some impact on the appeal of mechanical engineering research to students and the competitiveness of the discipline. Graduate students in mechanical engineering have been supported adequately over the past 20 years. During this time, graduate research assistantships have increased significantly. Research assistantships (RAs) accounted for more than 50 percent of graduate student support in 2004 (see Figure 3-8), with only a small number of fellowships. In comparison, chemical engineering graduate students received more than 50 percent of their support from RAs, with the rest of the support split nearly equal between fellowships, teaching assistantships (TAs), and other mechanisms.[19] Research assistantships for mechanical engineering graduate students have largely been supported by NSF, the Department of Defense (DOD) and other federal sources (see Figure 3-9). Chemical engineering graduate students also receive significant RA support from NSF and from other federal agencies. Chemistry graduate student RAs are supported by NSF, the National Institutes of Health (NIH), and other agencies.

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[19] National Research Council, 2007, *International Benchmarking of U.S.Chemical Engineering Research Competitiveness*, National Academies Press, Washington, D.C.

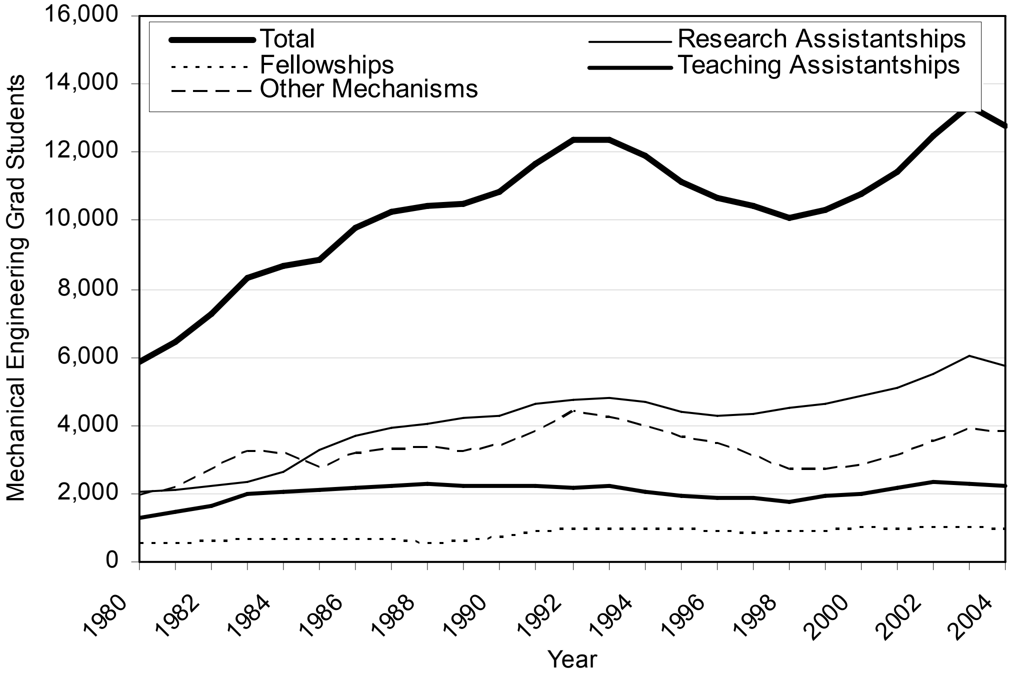

FIGURE 3-8 Full-time mechanical engineering graduate students by mechanism of support, 1980-2004.
SOURCE: NSF/SRS, *Survey of Earned Doctorates*, Integrated Science and Engineering Resources Data System (WebCASPAR), *http://webcaspar.nsf.gov* (accessed July 11, 2007).

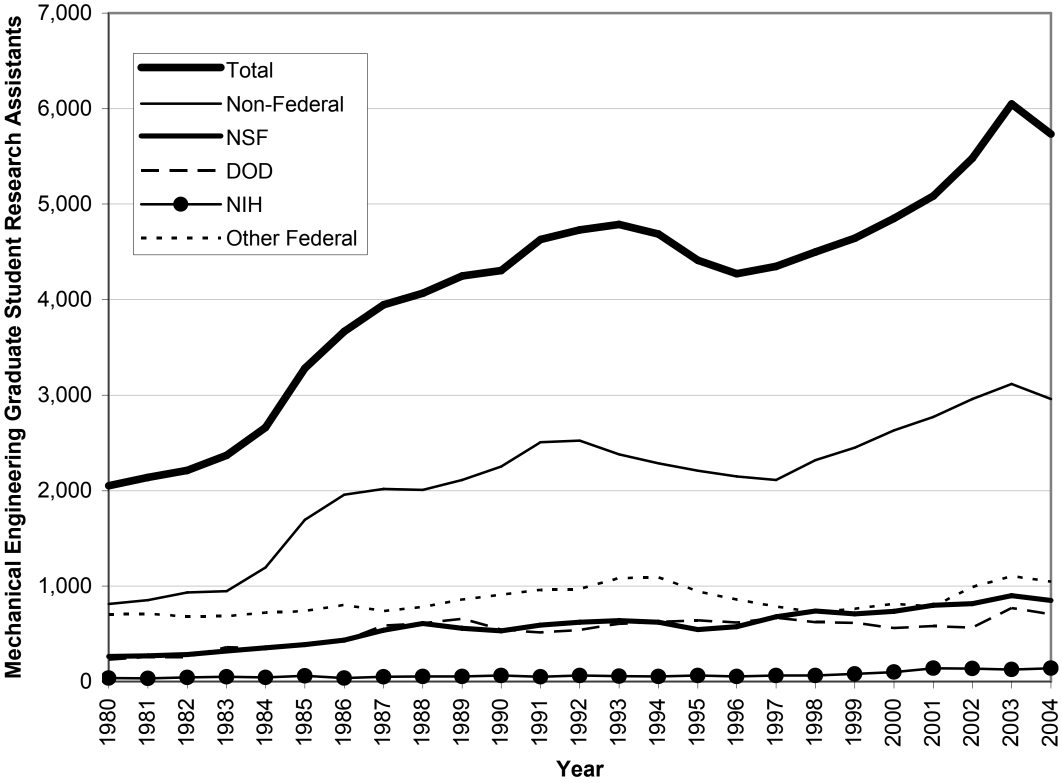

FIGURE 3-9 Full-time graduate students in mechanical engineering on research assistantships, by funding source. NOTE: Nonfederal is likely not directly from federal sources, whereas NSF, DOD, and NIH are directly funded graduate fellowships.
SOURCE: NSF/SRS, *Survey of Earned Doctorates*, Integrated Science and Engineering Resources Data System (WebCASPAR), *http://webcaspar.nsf.gov* (accessed September 5, 2006).

Favorable Job Prospects and Salaries for U.S. Mechanical Engineers

Employed mechanical engineering degree holders have steadily increased (Figure 3-10). The percentage change increase from 1999 to 2003 was 22 percent overall, 23 percent for bachelor's, 18 percent for master's, and 11 percent for Ph.D.s.

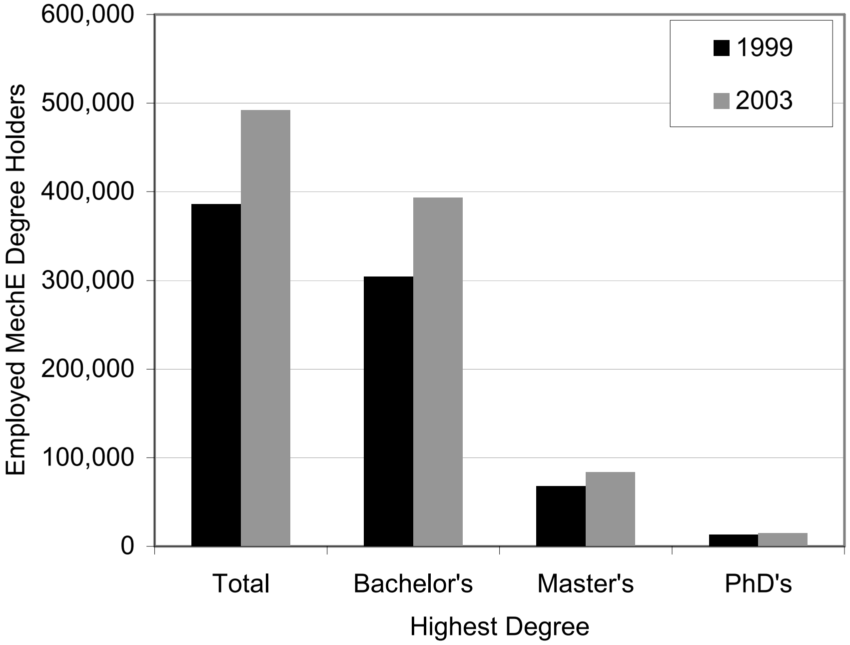

FIGURE 3-10 Comparison of employed mechanical engineering degree holders for 1999 and 2003.
SOURCE: NSF, *S&E Indicators*, 2004, 2006.

Figure 3-11 shows that there was an increase in the number of employed mechanical engineering degree holders across all employment sectors.

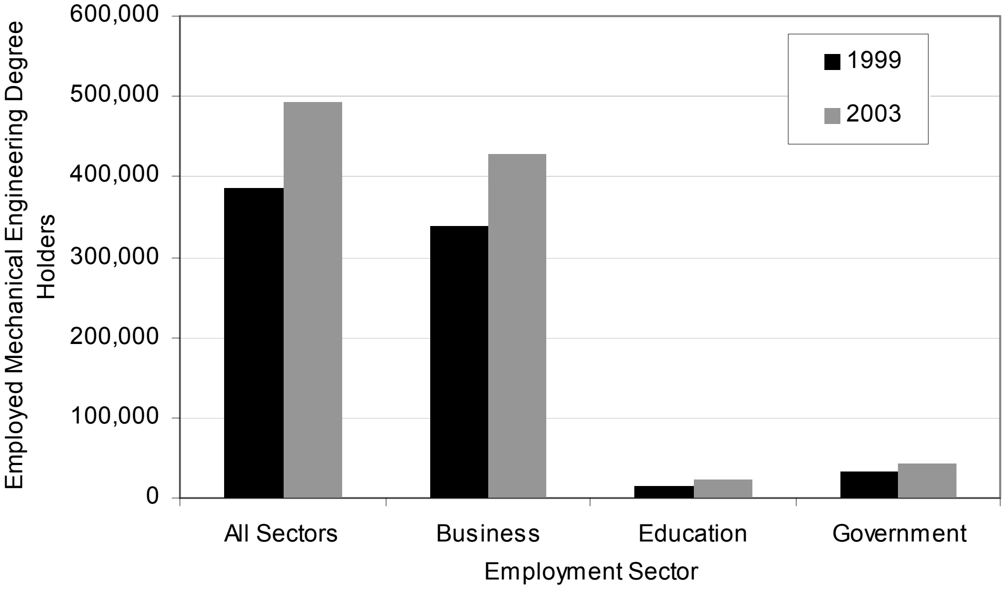

FIGURE 3-11 Comparison of employed mechanical engineering degree holders across different sectors for 1999 and 2003.
SOURCE: NSF, *S&E Indicators*, 2004, 2006.

According to the Bureau of Labor Statistics *2006-2007 Occupation Outlook Handbook*,[20] mechanical engineers can expect the following employment conditions:

> "Mechanical engineers [with S&E degrees) are projected to have an average rate of employment growth [9-17 percent] through 2014. Although total employment in manufacturing industries—in which employment of mechanical engineers is concentrated—is expected to decline, employment of mechanical engineers in manufacturing should increase as the demand for improved machinery and machine tools grows and as industrial machinery and processes become increasingly complex. Also, emerging technologies in biotechnology, materials science, and nanotechnology will create new job opportunities for mechanical engineers. Additional opportunities for mechanical engineers will arise because the skills acquired through earning a degree in mechanical engineering often can be applied in other engineering specialties."

The expected earnings for mechanical engineers are also quite good. While earnings for engineers vary significantly by specialty, industry, and education—engineers as a group earn some of the highest average starting salaries among those holding bachelor's degrees. Table 3-2 shows the average starting salary offers for engineers, according to the Fall *2007 Salary Survey* by the National Association of Colleges and Employers.

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[20] U.S. Department of Labor, Occupational Outlook Handbook, 2006-2007 Edition, Engineers, *http://www.bls.gov/oco/ocos027.htm* (accessed July 12, 2007).

TABLE 3-2 Average Starting Salary Offers for Engineers.

Curriculum	Bachelor's	Master's	Ph.D.
Aerospace, aeronautical, and astronautical	$53,626	$64,899*	$73,588*
Agricultural	49,866	61,100*	—
Bioengineering and biomedical	51,044	58,423*	—
Chemical	59,218	66,542*	76,688*
Civil	48,998	51,297	62,275*
Computer	55,920	67,304*	95,250*
Electrical, electronics, and communications	55,333	68,247	77,860*
Environmental and environmental health	47,914	—	—
Industrial/manufacturing	54,585	62,607	78,737*
Materials	53,056	—	—
Mechanical	54,057	63,209	70,928*
Mining & mineral (including geological)	52,624*	50,167*	—
Nuclear (including engineering physics)	55,966	62,848*	—
Petroleum	59,408*	57,000*	—

* Less than 50 offers reported

SOURCE: Reprinted from Fall 2007 *Salary Survey*, with permission of the National Association of Colleges and Employers, copyright holder.

Earnings for more experienced mechanical engineers (with Ph.D.s) as measured by median annual salary since degree (Figure 3-12), grew 3.1 percent annually between 1993 and 2003, which is 0.7 percent more than inflation.[21]

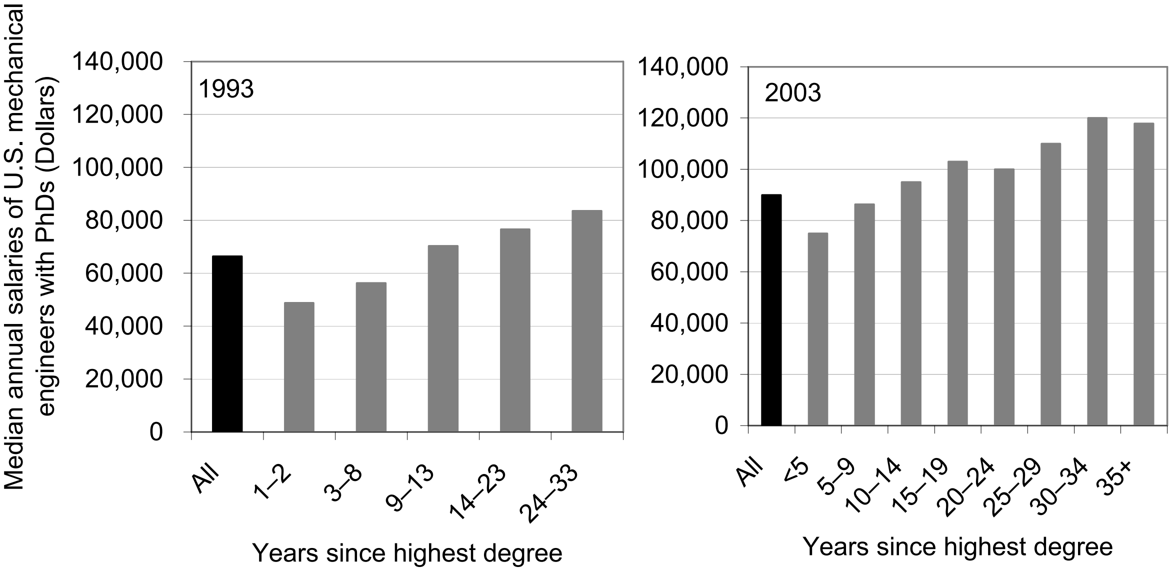

FIGURE 3-12 Median annual salaries for mechanical engineers with Ph.D.s by years since highest degree received, 1993 and 2003.
SOURCE: National Science Foundation/Science Resources Statistics, 1993 and 2003 *Survey of Doctorate Recipients*.

R&D FUNDING

Here the panel looks at trends in international levels and S&E funding and specific R&D funding for mechanical engineering in the United States. As discussed earlier, the U.S. innovation system benefits greatly from the variety as well as consistency of funding sources.

Steady Funding for S&E in the United States

The United States spent more on science and engineering R&D over 1981-2002 than any other OECD (Organisation for Economic Cooperation and Development) country (Figure 3-13). In 2003, the U.S. spent more than $250 billion (constant 2000 U.S. dollars) on total R&D.

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[21] The Consumer Price Index average annual increase for 1993-2003 was 2.42 percent. According to the Bureau of Labor Statistics Inflation Calculator, $1 in 1993 was equivalent to $1.27 in 2003.

About $50 billion of the U.S. expenditures were defense related (Figure 3-14), which is equivalent to Germany's total S&E expenditures. The United States accounted for more than 40 percent of the yearly international expenditures for S&E. Between 1981 and 2001, the U.S. contribution has declined from 45 percent to 43 percent, and the G7 contribution from 91 percent to 84 percent.

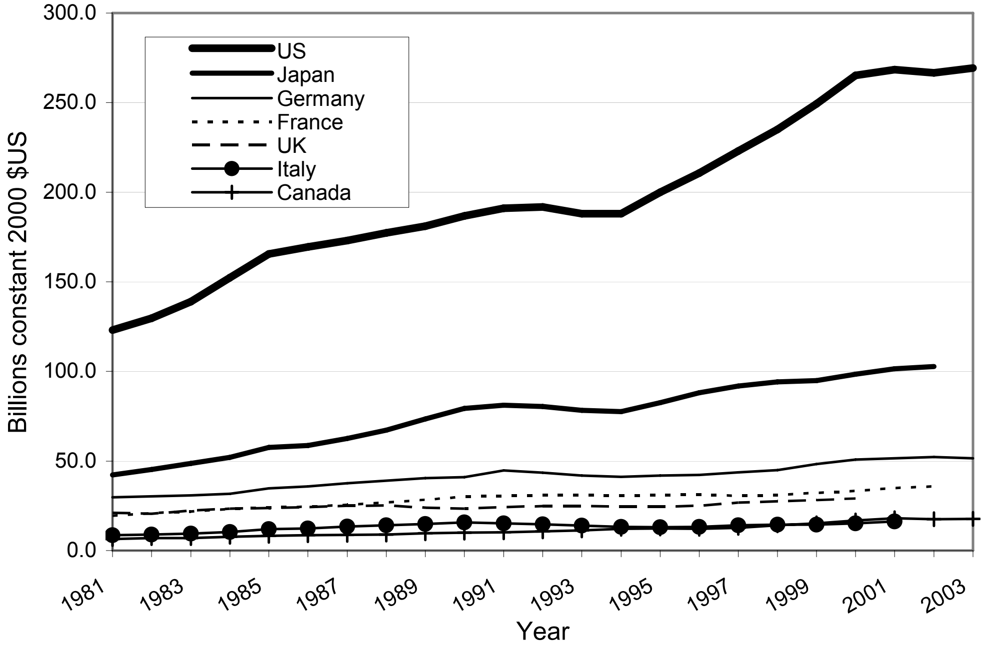

FIGURE 3-13 International R&D expenditures for G7 countries, 1981-2003 in billions of constant 2000 U.S. dollars.
SOURCE: NSF, *S&E Indicators 2006,* Appendix Table 4-42.

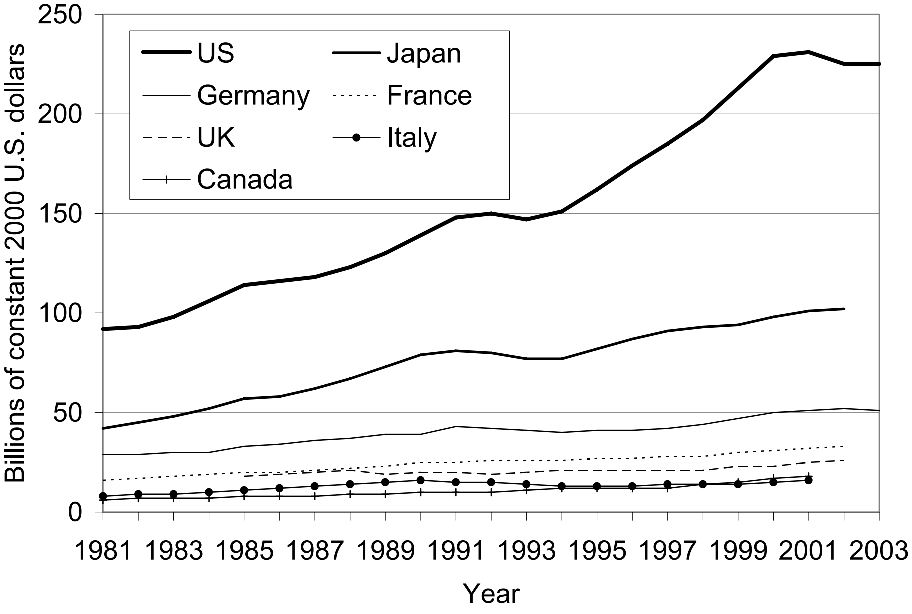

FIGURE 3-14 International nondefense R&D expenditures for select countries, 1981-2003. SOURCE: NSF, *S&E Indicators 2006,* Appendix Table 4-43.

The intensity of a nation's investment in S&E is better measured as a percentage of its gross domestic product (GDP) spent on R&D. In 2003 the United States spent a smaller percentage of its GDP (2.2 percent) on nondefense R&D than either Japan (3.1 percent) or Germany (2.5 percent; see Figure 3-15). The European Union has a stated goal of spending 3.0 percent of GDP on research. In December 2006 the European Parliament approved the Seventh Framework Program, a 55 billion Euro, seven-year package to increase the research budget by 40 percent.[22]

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[22] M. Enserink, 2006, "European Research: Unprecedented Budget Increase Draws Faint Praise," *Science,* 314(5805):1523-1525.

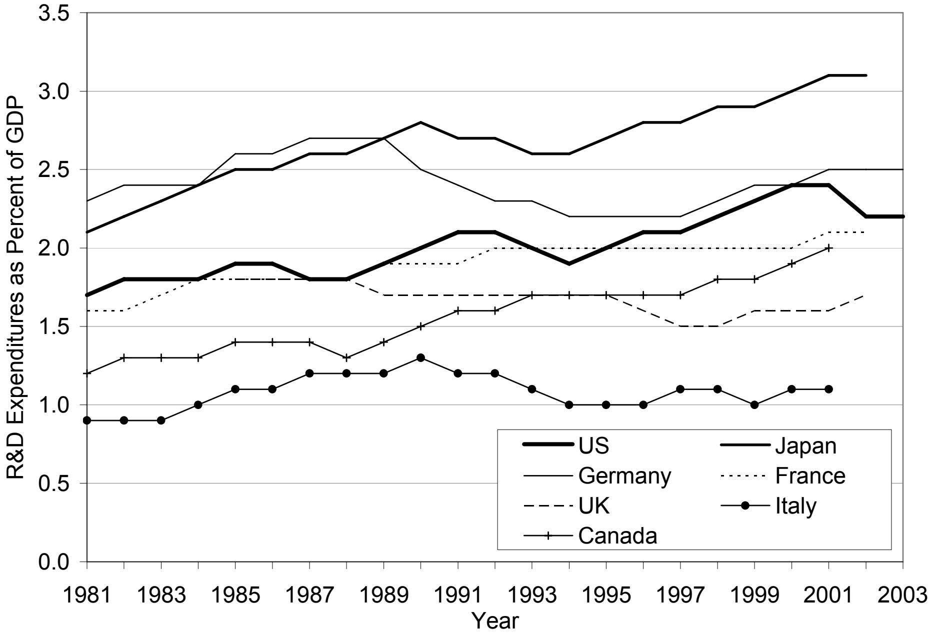

FIGURE 3-15 International nondefense R&D as percentage of GDP, by selected country, 1981-2003.
SOURCE: NSF, *S&E Indicators 2006,* Appendix Table 4-43

Steady, but Unbalanced U.S. Funding for Mechanical Engineering

In 2005, reported academic spending on mechanical engineering R&D totaled more than $900 million (Figure 3-16). Of this, about two-thirds consisted of federal sources.

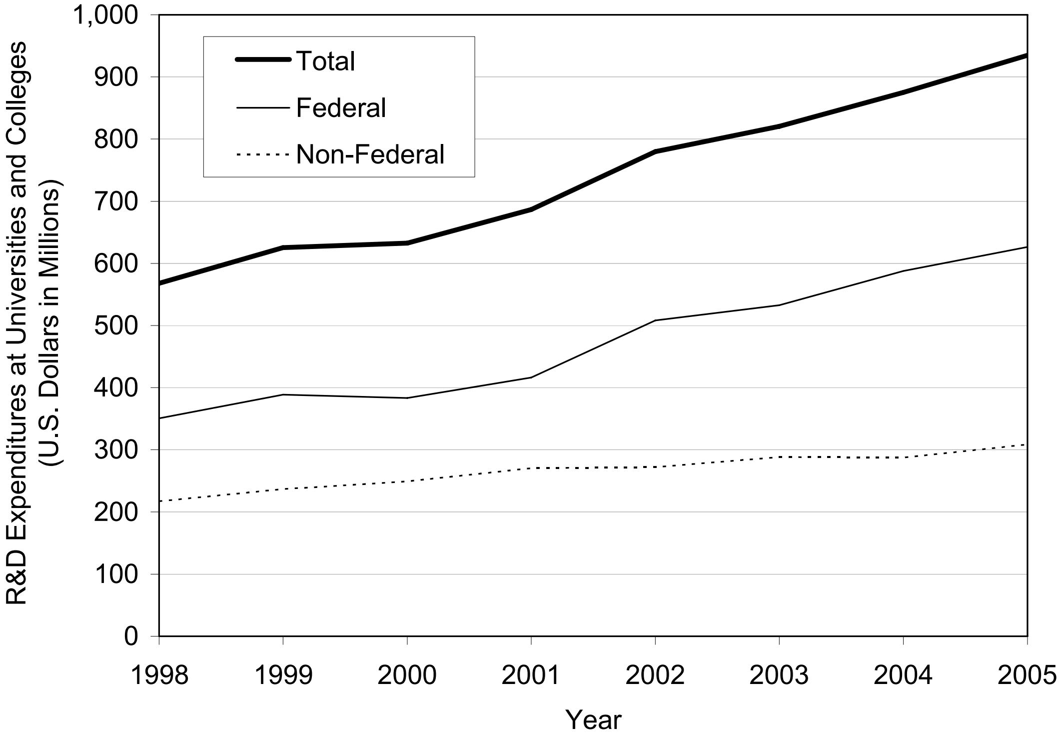

FIGURE 3-16 Federal and nonfederal R&D expenditures at academic institutions in mechanical engineering. Nonfederal expenditures include state and local government, industry, institutionally, and other financed academic R&D expenditures.
SOURCE: NSF/SRS, *Survey of Research and Development Expenditures at Universities and Colleges*, FY 2004.

In terms of constant 2000 dollars, the reported U.S. federal government funding (obligations)[23] for total research in mechanical engineering declined from a high of almost $550 million in 1993 to just over $250 million in 2003 (Figure 3-17), which is similar to levels in the early 1980s. There could be multiple reasons for this decline. One that has been documented in the past has to do with changes in NSF classification of funding by field of research, which changed in 1996.[24] Federal obligations for mechanical engineering over the period 1999-2003 were on average about 1 percent of the total U.S. R&D budget.

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[23] Inconsistencies are known to exist between reported university research "expenditures" and federal government research "obligations." For a detailed analysis and discussion of how research funding is reported, see the following report: National Research Council. 2001. *Trends in Federal Support of Research and Graduate Education*, National Academy Press, Washington, D.C.

[24] National Research Council. 2001. *Trends in Federal Support of Research and Graduate Education*, National Academy Press, Washington, D.C.

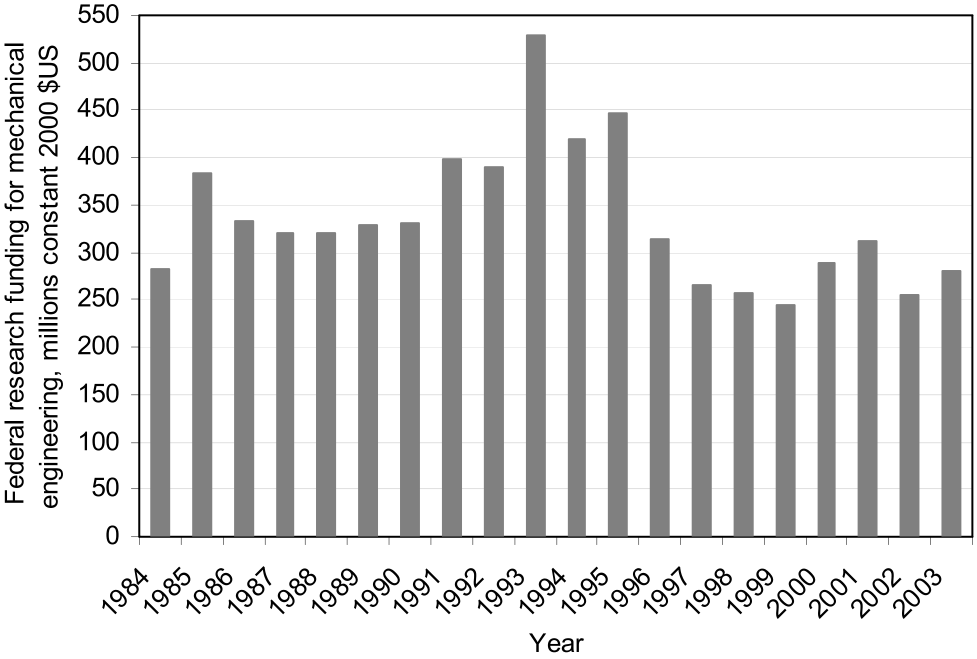

FIGURE 3-17 Federal obligations for total research in mechanical engineering.
SOURCE: NSF, *S&E Indicators 2006,* Appendix Table 4-32

Federal funding for mechanical engineering research is comparable with spending for the other “big four” engineering fields of civil and chemical engineering, with the exception of electrical engineering, which has traditionally been better funded than chemical, civil, and mechanical engineering (Figure 3-18).

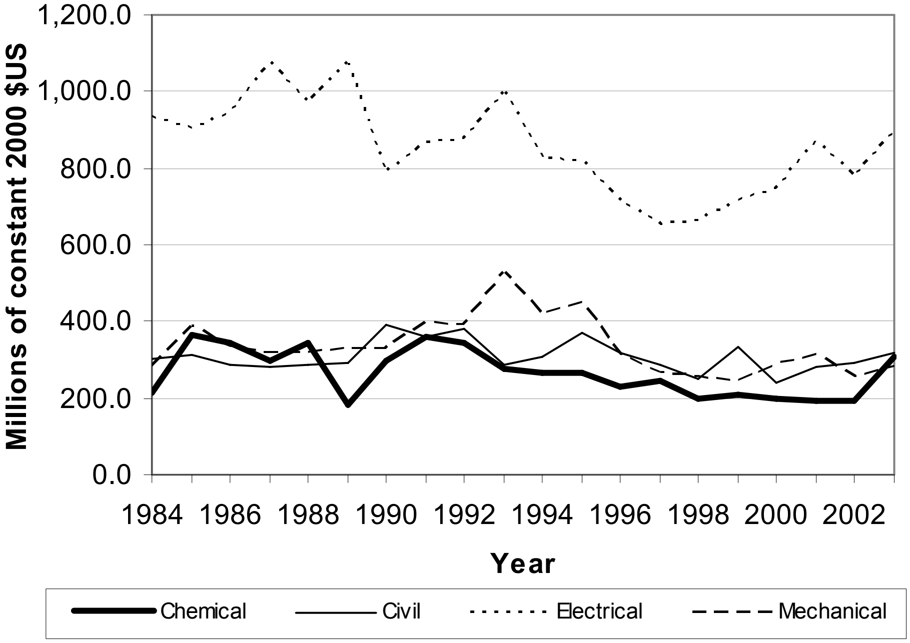

FIGURE 3-18 Federal obligations for total research, by engineering field: FY 1984-2003.
SOURCE: NSF, *S&E Indicators 2006,* Appendix Table 4-32

DOD has accounted for the largest proportion of federal obligations for mechanical engineering research over the years (Figure 3-19). However, in the past, other agencies accounted for a larger proportion, especially for basic research (Figure 3-20). In 1994 DOD accounted for 70 percent of the federal obligations for mechanical engineering research, whereas in 2004, DOD accounted for 84 percent.

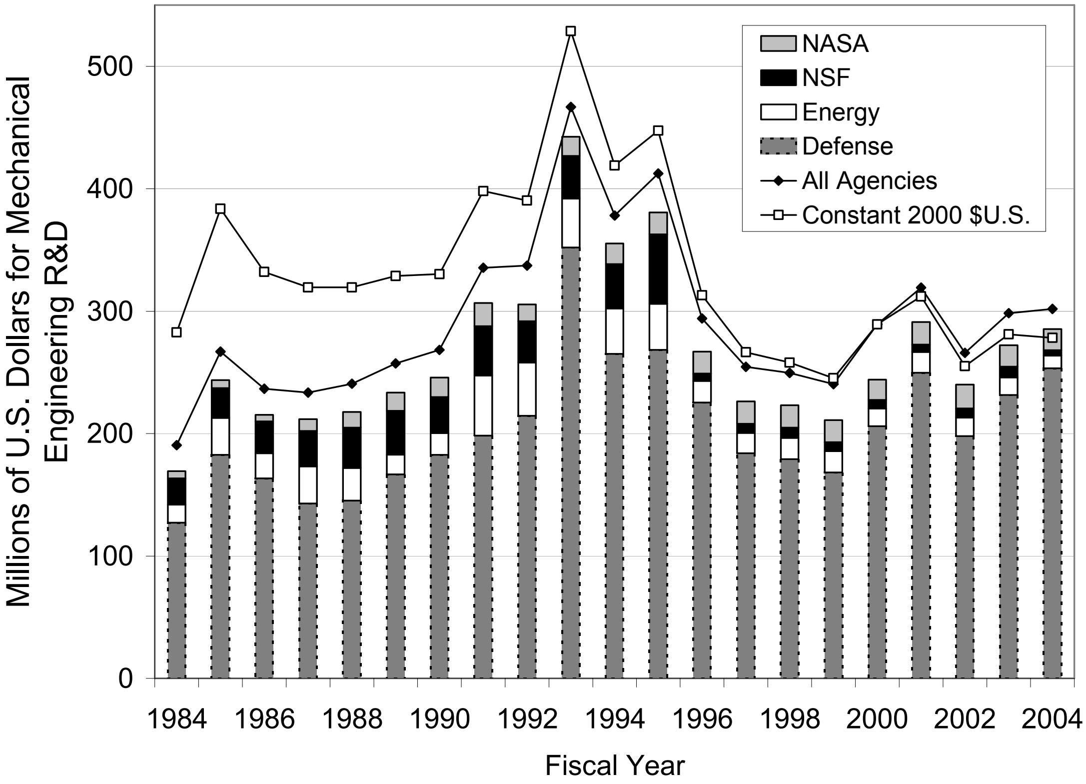

FIGURE 3-19 Federal obligations for total research in mechanical engineering, 1984-2004. SOURCE: NSF, *Federal Funds for R&D, http://www.nsf.gov/statistics/fedfunds/* (accessed July 12, 2007).

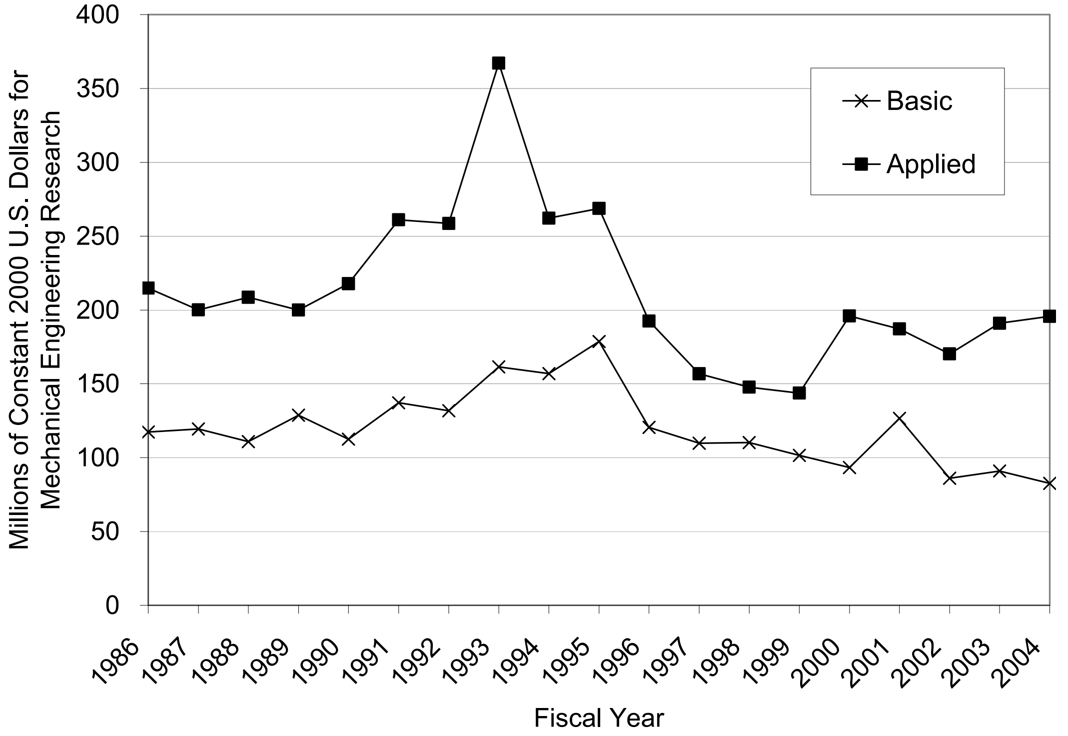

FIGURE 3-20 Federal obligations for applied versus basic research in mechanical engineering in constant 2000 U.S. Dollars, fiscal years 1986-2004.
SOURCE: NSF, *Federal Funds for R&D, http://webcaspar.nsf.gov* (accessed September 19, 2007).

The dominance of DOD funding for mechanical engineering is significant for basic research, because other agency contributions have been diminished (Figure 3-21). NSF in particular contributed significantly less in 2004 than in 1994. The dominance of a single agency has likely created uneven funding opportunities in mechanical engineering.

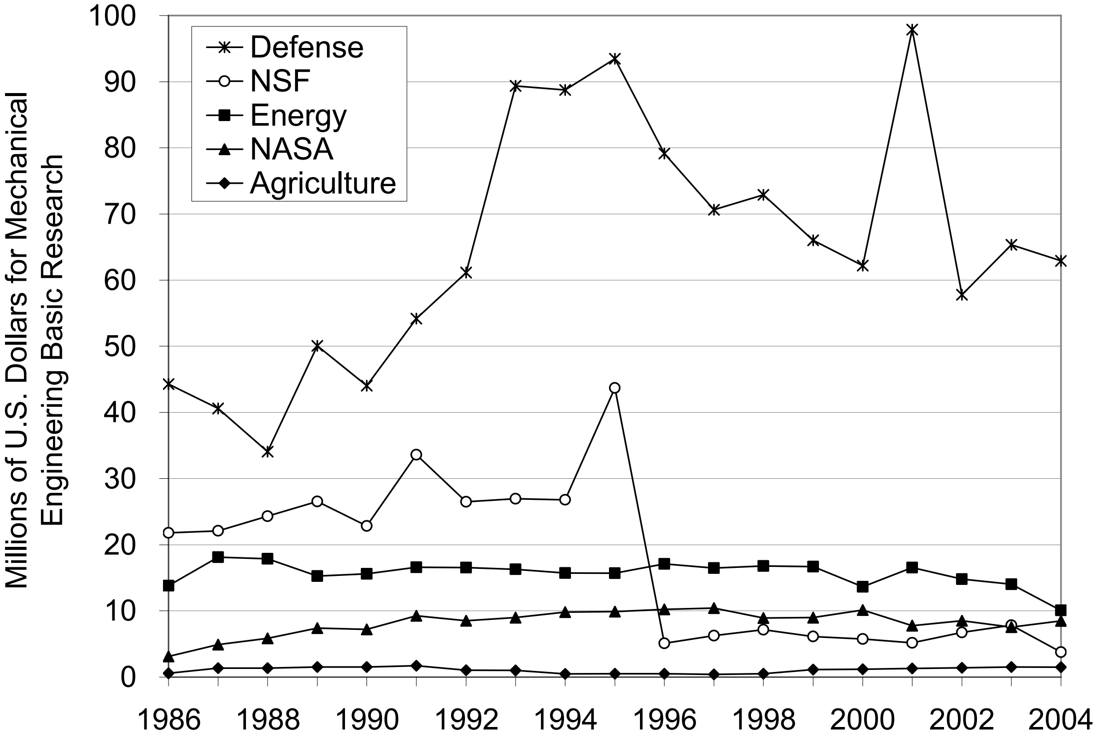

FIGURE 3-21 Federal obligations for Basic Research in Mechanical Engineering by Agency for Fiscal Years 1986-2004.
SOURCE: NSF, *Federal Funds for R&D, http://webcaspar.nsf.gov* (accessed September 19, 2007).

DOD obligations for basic research in mechanical engineering largely come from the Air Force, Army, and Navy (Table 3-3). Specific information on the breakdown of DOD funding for specific areas of mechanical engineering is not readily available, but the type of mechanical engineering research funded is described on the various DOD organization websites. According to the Army Research Office website,[25] "it supports fundamental investigations in the areas of solid mechanics, structures and dynamics, combustion and propulsion, and fluid dynamics." The Air Force Office of Scientific Research website[26] indicates it supports "A wide range of fundamental research addressing structures, structural materials, solid mechanics, fluid dynamics, propulsion, and chemistry."

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[25] *http://www.arl.army.mil/www/default.cfm?Action=29&Page=187* (accessed September 18, 2007)

[26] *http://www.afosr.af.mil/ResearchAreas/research_aero.htm* (accessed September 18, 2007)

TABLE 3-3 U.S. Department of Defense Obligations for Mechanical Engineering Research (U.S. Dollars in thousands)

	1994			2004		
	Total	Basic	Applied	Total	Basic	Applied
Total	252,999	76,705	176,294	253,400	62,901	190,499
Defense agencies	33,876	20	13,876	14.391	2,172	12,219
Defense Advanced Research Projects Agency	372	0	372	10,750	0	10,750
Balistic Missile Defense	12,165		12,165			
Defense Nuclear	1,339		1,339			
Washington Headquarters Services	20,000	20,000	0	3,641	2,172	1,469
Air Force	33,789	11,646	22,143	34,727	7,696	27,031
Army	97,517	13,586	83,931	147,973	26,962	121,011
Navy	87,817	31,473	56,344	56,309	26,071	30,238

SOURCE: National Science Foundation, *Survey of Federal Funds for Research and Development*, 1994 and 2004.

Other federal agencies also vary in the specific information they provide on the breakdown of funding for specific areas of mechanical engineering. Below is a comparison of Department of Energy Basic Energy Sciences funding for core research areas in materials (Figure 3-22) for fiscal year 2001 and fiscal year 2005, which includes the core research area of mechanical behavior and radiation effects. According to DOE, "This activity supports basic research to understand the deformation, embrittlement, fracture, and radiation damage of materials with an emphasis on the relationships between mechanical behavior and radiation effects and defects in the material. This research builds on atomic level understanding of the relationship between mechanical behavior and defects in order to develop predictive models of materials behavior for the design of materials having superior mechanical behavior such as at very high temperatures."

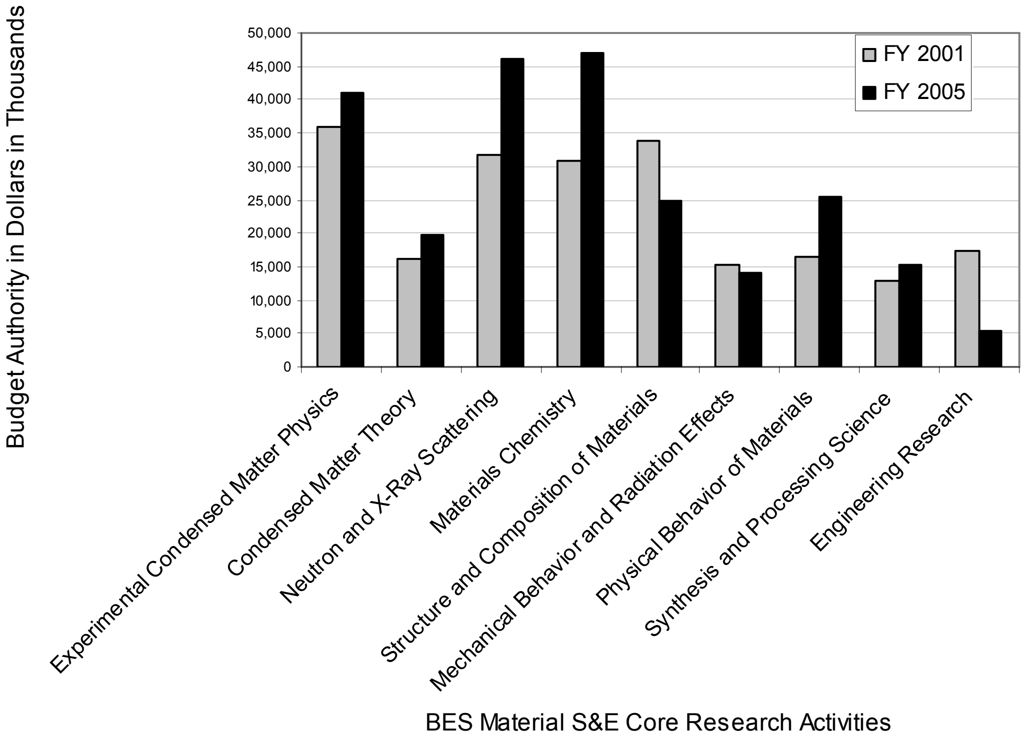

FIGURE 3-22 Department of Energy Basic Energy Sciences Funding for Material Science and Engineering Core Research Activities.
SOURCE: *http://www.er.doe.gov/bes/brochures/CRA.html*.

Figure 3-23 shows the breakdown for funding for the NSF Engineering Directorate. NSF support for mechanical engineering research comes largely from Civil, Mechanical and Manufacturing Innovation (CMMI) Division. CMMI funds research in a various areas of mechanical engineering, including architectural and mechanical systems, dynamics and control systems, manufacturing machines and equipment, mechanics and structure of materials, and nano/bio mechanics. Mechanical engineering basic research in thermal systems and fluid mechanics, as well as a work in micro- and nanofluids and heat transfer is funded by CBET.

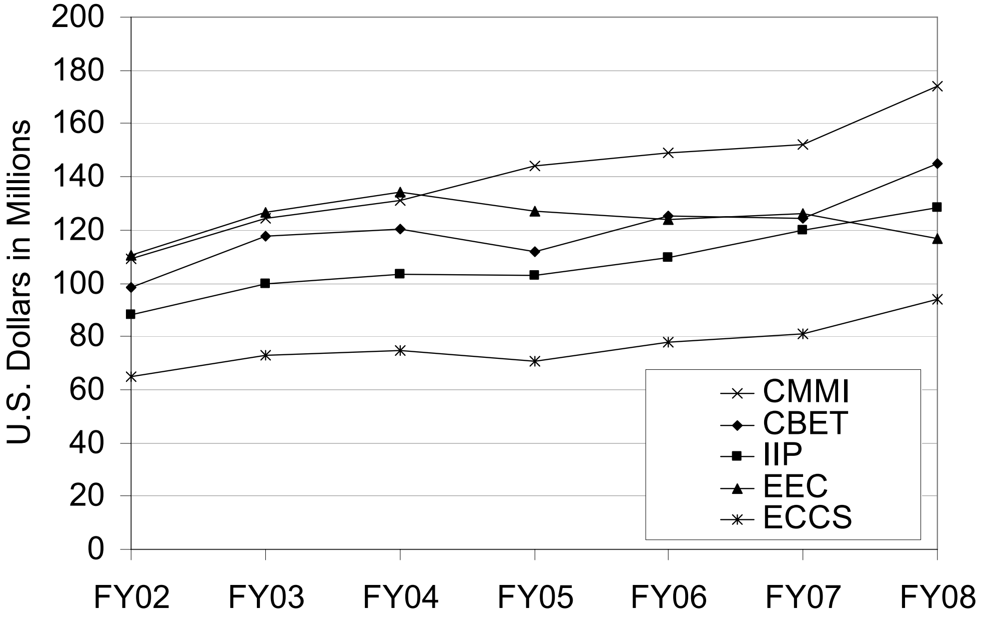

FIGURE 3-23 NSF Engineering Directorate funding for divisions in millions of U.S. dollars: Civil, Mechanical and Manufacturing Innovation (CMMI); Chemical, Bioengineering, Environmental and Transport Systems (CBET); Industrial Innovation and Partnerships (IIP); Engineering Education and Centers (EEC); and Electrical, Communications and Cyber Systems (ECCS).
NOTE: FY2007 and FY2008 are proposed budgets.
SOURCE: NSF fiscal year 2008 budget request, available at *http://www.nsf.gov/about/budget* (accessed July 12, 2007).

Table 3-4 shows the overall research proposal funding rate for CMMI. While, the number of awards has remained fairly stable and the median annual size of awards has increased between 1997 and 2006, the funding rate for awards has decreased by 11 percent, from 28 percent in 1997 to 17 percent in 2006.[27] The funding rate for awards in CBET decreased by 13 percent, from 30 percent in 1997 to 17 percent in 2006. In comparison, the funding rate for the NSF engineering directorate and NSF as a whole declined by only 8 percent during this same time period. Comparable data on proposal funding rates for other funding agencies were not readily available.

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[27] NSF Budget Internet Information System, *http://dellweb.bfa.nsf.gov/*

TABLE 3-4 Research Proposal Funding Rate for NSF CMMI Division, FY 1997 to 2006

FY	No. of Proposals	No. of Awards	Funding Rate (%)	Median Annual Size
2006	2,860	478	17	$83,332
2005	2,644	475	18	$81,700
2004	2,576	515	20	$78,000
2003	2,618	515	20	$79,916
2002	2,418	489	20	$74,076
2001	2,205	403	18	$72,000
2000	1,891	480	25	$66,711
1999	1,514	422	28	$62,017
1998	1,753	383	22	$59,335
1997	1,574	434	28	$60,522

SOURCE: NSF Budget Internet Information System, *http://dellweb.bfa.nsf.gov/* (accessed July 12, 2007).

SUMMARY

U.S. research leadership in mechanical engineering basic research is the result of a combination of key factors, including a national instinct to respond to external challenges and to compete for leadership. Over the years, the United States has been a leader in innovation as a result of cutting-edge facilities and centers, and a steady flow of mechanical engineers and research funding.

- Major centers and facilities provide key infrastructure and capabilities for conducting research and have provided the foundation for U.S. leadership. Key capabilities for mechanical engineering basic research include the following
    - Measurement and standards
    - Materials characterization and micro- and nanofabrication
    - Manufacturing and automation
    - Biomechanical engineering
    - Supercomputing and cyberinfrastructure
    - Small- and large-scale flow systems
- There is increasingly strong competition for international science and engineering human resources. The United States has maintained a steady supply of Ph.D. mechanical engineering graduates over the years. This is largely the result of increased reliance upon foreign-born students. Between 1997 and 2005, the number of U.S. citizens who received mechanical engineering Ph.D. degrees declined 35 percent.

- Research funding for S&E overall and mechanical engineering in particular has been steady. In 2005, more than $900 million was spent on mechanical engineering R&D at academic institutions. Of this, about two-thirds were federal expenditures. Federal support for U.S. mechanical engineering research between 1999 and 2003 was on average about one percent of the total U.S. R&D budget, with the largest portion (more than 70 percent) coming from DOD.

4

The Likely Future Position of U.S. Mechanical Engineering Basic Research

Earlier in the report the panel assesses the current position of U.S. research in mechanical engineering relative to that in other regions or countries (Chapter 2) and identifies the key factors influencing relative U.S. performance in mechanical engineering (Chapter 3). In this final chapter of the report, the panel addresses the third part of its charge—to determine the relative position of U.S. mechanical engineering in the near term and in the longer term.

In short, U.S. mechanical engineering is currently in a healthy position and will likely continue to be in the near future. Mechanical engineering makes many significant contributions to U.S. economic competitiveness and national quality of life; broad public benefits are now derived from past investments in mechanical engineering—for example, in the transportation, power generation, and aviation industries.

If no major change occurs in U.S. science policy or levels of financial support, mechanical engineering research in the United States will remain among the leaders for at least the next five years. However, there will continue to be increasing competition from Europe and Asia. Analysis of data in Chapters 2 and 3 reveals trends in U.S. mechanical engineering that the panel believes are likely to continue in the near- (two to three years) and mid-term (five to seven years) future.

Over the past decade, graduate enrollment and the number of new U.S.-trained Ph.D.s has been virtually constant, and federal research support for mechanical engineering research has barely kept up with inflation. In contrast, the number of Ph.D.s trained outside the United States continues to increase. The number of papers published by non-U.S. authors in both international and ASME journals is increasing. Based on flat U.S. mechanical engineering research budgets and flat numbers of students, the panel projects that other nations and regions will soon be catching up or passing the United States.

Projected trends in mechanical engineering publications, human resources, research funding, and infrastructure are presented below.

MECHANICAL ENGINEERING RESEARCH PUBLICATIONS

The number of mechanical engineering articles by U.S. authors will continue to increase over the next several years, but the share of mechanical engineering articles from U.S. authors will continue to decrease due to likely increases in the number of articles from other countries. The quality of international mechanical engineering research is also increasing, and the panel projects that this will be reflected in increased citations per paper for non-U.S. authors and in a decrease in the U.S. lead in citations per paper. Similarly, the fraction of most-cited articles coming from non-U.S. authors is expected to increase.

SUPPLY OF U.S. MECHANICAL ENGINEERS

The number of mechanical engineering Ph.D.s trained in the United States was more than 800 per year for 1995-2005. In 1980, there was about half this number of Ph.D.s. However, over this time, the number of U.S. citizens receiving mechanical engineering Ph.D.s has steadily decreased. The number of U.S. mechanical engineering graduate students has been maintained by successfully attracting international students to the United States. Many of these students often stay in the United States after graduation and pursue careers in mechanical engineering. Evidence of the attractiveness of the United States is the high percentage of foreign doctorate recipients who plan to remain in the United States for work after graduation (Table 4-1).

However, with changes in visa policies as a result of the attack on 9/11 (Figure 4-1) and global leveling of research capability, the United States may be losing ground. Following 9/11, international students and postdoctoral associates found it increasingly difficult to obtain visas for study in the United States and many traveled to Europe, Japan, and Australia for their graduate work. This has had a fairly significant impact on engineering disciplines compared to the sciences, which also holds for mechanical engineering as shown in Figure 3-5 (ratio of Ph.D.s to temporary residents decreased three years in a row for 2003-2005). Also, because of the growth of new opportunities for Ph.D. mechanical engineers in China, India, and elsewhere, more students who obtain a U.S. Ph.D. are increasingly likely to return to careers in their native countries or to other opportunities elsewhere. Thus, the United States is faced with increasing competition overall for attracting foreign graduate students and for retaining them in the U.S. workforce.

It is not clear whether the United States can continue to attract mechanical engineering talent from the United States and abroad in the future. According to a background paper generated for the recently held NSF “5XME” workshop,[1]

> Many countries now emulate the very successful USA engineering schools and their science-based curricula, and are making investments that produce an order of magnitude more engineers, and of comparable quality. Global companies employ such world-class engineering talent, often at 20% of the cost in the USA and are moving manufacturing design and even research activities to such locations.

The authors state that “the challenge for engineering schools in the U.S. is how to educate a mechanical engineer that provides five times the value added when compared to the global competition, i.e., the ‘5XME.’”

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[1] 5XME White Paper -- The “5XME” Workshop: Transforming Mechanical Engineering Education and Research in the USA, M.L. Good, M. Jones, L. Matsch, C.D. Mote, Jr., and A.G. Ulsoy, 3/16/07; workshop held May 10-11, 2007; www.umich.edu/~ulsoy/5XME.htm

A recent study from Duke University[2] points out that the large numbers of engineers graduating in China and India are not necessarily equivalent to U.S. graduates and that "rather than trying to match their demographic numbers and cost advantages, the United States needs to force competitors to match its ability to innovate." Thus, the right balance between the quantity and quality of mechanical engineering graduates is likely the key to future U.S. research competitiveness.

TABLE 4.1 Percentages of Foreign Doctorate Recipients Planning to Stay in the United States after Graduation, 1994-2003.

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Definite plans to stay	34	35	42	44	46	49	49	54	52	48
Plans to stay	62	65	67	68	67	70	71	74	73	71

SOURCE: Special tabulation of Data from the *Survey of Doctorate Recipients*, prepared by National Opinion Research Center.

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[2] Wadhwa, V; G. Gereffi; B. Rissing; and R. Ong, "Where the Engineers Are" *Issues in Science and Technology*, Spring 2007.

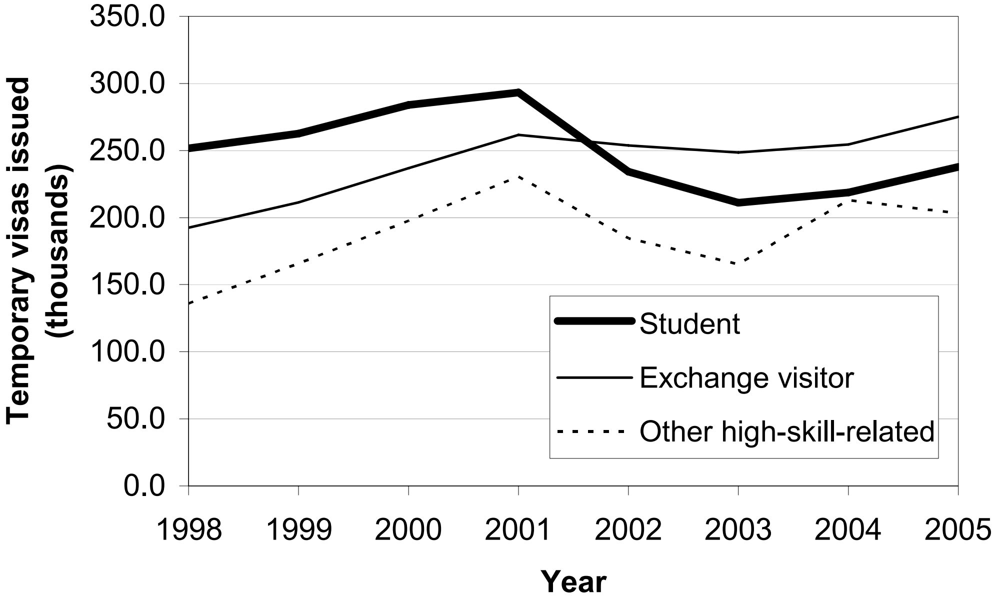

FIGURE 4-1 Student, exchange visitor, and other high-skill-related temporary visas issued, 1998-2005.
SOURCE: NSF, *Science & Engineering Indicators* 2006.

U.S. MECHANICAL ENGINEERING RESEARCH FUNDING

University reported mechanical engineering research expenditures has continued to grow over the years, and reached more than $900 million in 2005. Federal sources have made up an increasingly larger percentage of these expenditures, which will likely continue.

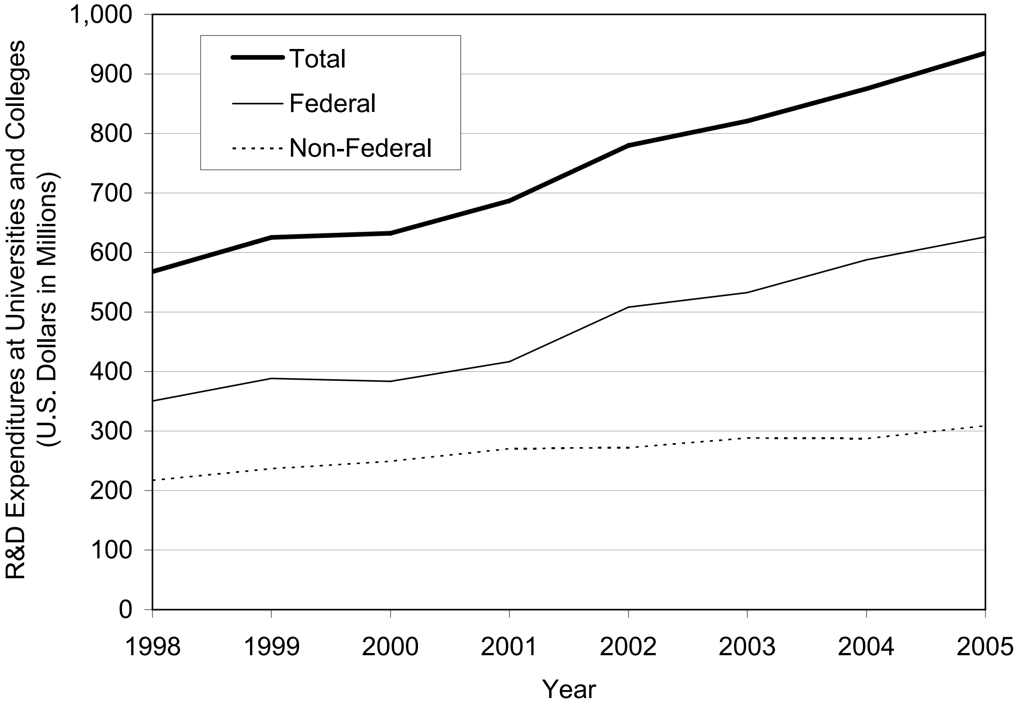

FIGURE 4-2 Federal and nonfederal R&D expenditures at academic institutions in mechanical engineering.
SOURCE: NSF/SRS, *Survey of Research and Development Expenditures at Universities and Colleges*, FY 2004.

On the other hand, federal government reported obligations[3] for mechanical engineering research over the past 10 years (in constant 2000 dollars) have been flat, and funding for basic research has declined (Figure 4-3). In addition, funding has been dominated by a single agency, DOD. If this funding trend continues, U.S. mechanical engineering basic research will likely drop from a leadership position among the leaders to lagging behind the leaders.

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[3] Inconsistencies are known to exist between reported university research "expenditures" and federal government research "obligations." For a detailed analysis and discussion of how research funding is reported, see the following report: National Research Council. 2001. *Trends in Federal Support of Research and Graduate Education*, National Academy Press, Washington, D.C.

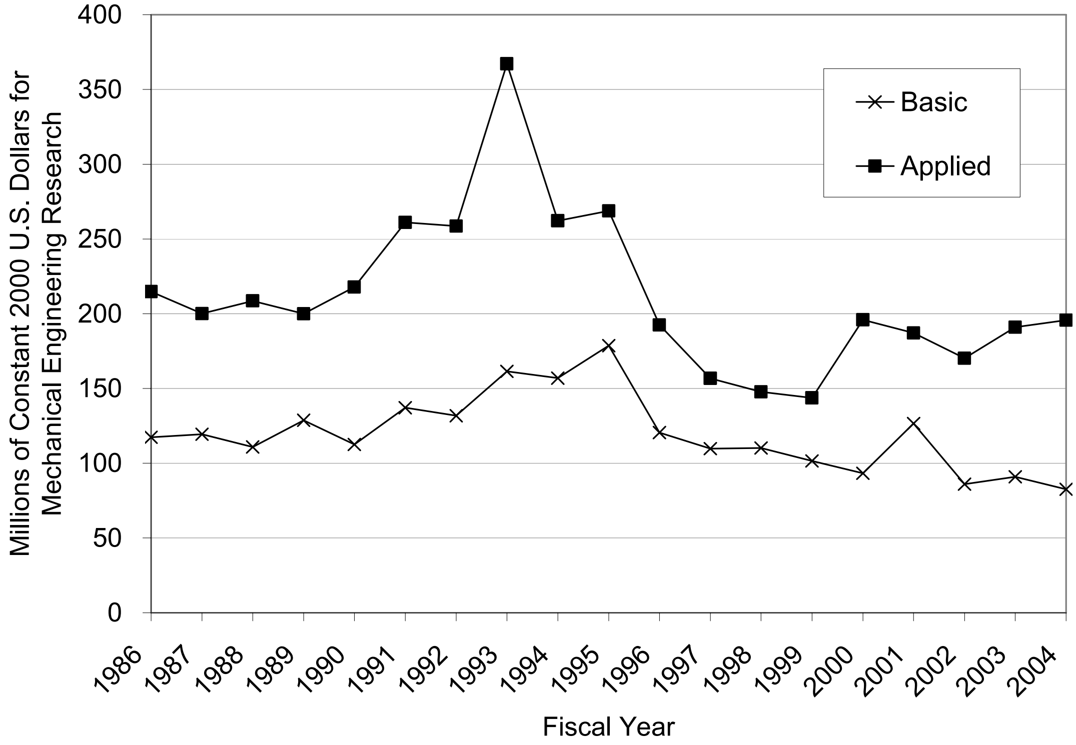

FIGURE 4-3 Federal obligations for applied versus basic research in mechanical engineering in constant 2000 U.S. Dollars, fiscal year 1986-2004.
SOURCE: NSF, *Federal Funds for R&D, http://webcaspar.nsf.gov* (accessed September 19, 2007).

INFRASTRUCTURE TO SUPPORT BASIC RESEARCH

The quality of the basic research infrastructure strongly influences the long-term health of mechanical engineering research. The position of the U.S. research enterprise will be strongly influenced by the improvement or decline of this infrastructure, which includes organizational structure and intellectual property policies in addition to facilities and instrumentation.

The university structure in which the mechanical engineering organization resides strongly influences the future of the discipline. The high quality of U.S. academic leadership in mechanical engineering and the excellence of the scientific research enterprise have placed mechanical engineering departments in a position of strength at most of the top research universities in the United States. The prominence of mechanical engineering in industry and government agencies is also well established.

Mechanical engineers require instruments for daily use and access to major frequently used instruments in their local departments. Mechanical engineering research sometimes requires major instruments or facilities that can only be economically provided by national facilities.

Major centers and facilities provide key infrastructure and capabilities for conducting research and have provided strong support for U.S. leadership in mechanical engineering. Key capabilities for mechanical engineering research include advanced light sources, scanning probe instruments, supercomputers, nuclear reactors and accelerators, and specialized facilities for biomechanics. U.S. facilities have instrumentation that is on par with the best in the world. However, rapid advances in the design and capabilities of instrumentation can create obsolescence in five to eight years. Large central facilities must continuously be upgraded and maintained. Sustained support is essential to compete with heavy capital investments by the European Union, Japan, Korea, and China.

Federal laboratories and the national laboratories of DOE are critical in providing unique facilities for research; they have instrumentation no single university could afford to put in place. An important complement is the availability of world-class scientists who engage in long-term fundamental research and provide assistance through research collaborations with the user community.

Although the United States has enjoyed a research and funding environment that has enabled the installation and operation of a diverse range of facilities to support leading-edge research in mechanical engineering, funding for needed infrastructure seems to be in continuous jeopardy.

For example, U.S. research infrastructure includes major user facilities such as the National Solar Thermal Test Facility, the AZTRAK (AZimuthal TRAcKing) Rotating Platform system and the Combustion Research Facility (centering on improving energy efficiency and reducing emissions from energy conversion and utilization systems) at Sandia Labs, and NIST's Building Integrated Photovoltaic Testbed and Mobile Solar Tracking Facility. All of these are based on technology needs from the 1980s, and major facilities in Europe and Japan are overshadowing U.S. capability to demonstrate and gain experience in large-scale systems. A few examples include the Japanese High Temperature Gas Reactor, the European Solar Thermal Industry Federation (ESTIF) in Brussels, and the European Solar Test Installation (ESTI) in Ispra, Italy.

SUMMARY

The United States now holds a leadership position in most areas of mechanical engineering basic research. However, because of the advance of mechanical engineering in other nations, competition is increasing and the U.S. lead will shrink. The United States is particularly strong in emerging areas at the interface with other disciplines. In these areas, which include biomechanical engineering, design, and mechanics of materials, the United States will maintain a leadership position in spite of growing competition. In some core areas where the U.S. position is currently not as strong such as acoustics and dynamics, dynamic systems and controls, computational mechanics, and tribology, U.S. leadership may continue to face further challenges from other nations. In the areas where the United States is currently the leader in research, bioengineering, design, manufacturing, mechanics of engineering materials, and thermal systems and heat transfer, U.S. leadership should remain strong.

On the basis of current trends in the United States and abroad, the relative future U.S. position in mechanical engineering basic research is outlined below:

- There will be growing industrial opportunities in China and India, which will result in increased mechanical engineering research talent and leadership abroad.

- There will likely be continued movement offshore of mechanical engineering R&D by U.S. companies, as well as increased competition from foreign companies. Local talent will be hired, which will likely include international students educated and trained in the United States.
- There will also be more international research collaborations (United States and other countries, between countries in the European Union, etc.)
- U.S. universities will continue to reach out and offer educational opportunities abroad and online. For example, the Singapore-MIT alliance (SMA)[4] founded in 1998 is an engineering education and research collaboration among the National University of Singapore (NUS), Nanyang Technological University (NTU), and the Massachusetts Institute of Technology (MIT). Online there is the international multi-university OpenCourseWare Consortium.[5] If the United States does not continue such outreach efforts, other countries certainly will.
- Contemporary issues such as national security, energy, manufacturing competitiveness, sustainability will be a strong influence on research directions in mechanical engineering. These are areas in which mechanical engineering can make significant contributions.
- Going forward, there will be a continued emergence of certain fields such as MEMS, nanotechnology, mechatronics, alternative energy sources, biomedical materials and devices, green manufacturing, and materials over many length scales. In addition, there will be continued importance of high-technology fields in which the United States maintains a strong leadership position, such as the design and manufacturing of civilian and military aircraft, healthcare diagnostics, and power generating systems.
- U.S. academic mechanical engineering departments continue to attract international talent for graduate studies; however, the barriers to travel for international students and visiting faculty may impact the ability of the United States to continue to attract this important source of research talent.

In conclusion, U.S. leadership in mechanical engineering overall will continue to be strong. The contributions of U.S. mechanical engineers to journal articles will increase, but so will the contributions from other growing economies such as China and India. At the same time, the supply of U.S. mechanical engineers is in jeopardy, due to declines in the numbers of U.S. citizens obtaining advanced degrees and uncertain prospects for continuing to attract foreign students. U.S. funding of mechanical engineering research and infrastructure will remain level, with strong leadership in emerging areas.

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[4] *http://web.mit.edu/sma/* (accessed September 26, 2007)

[5] *http://www.ocwconsortium.org/about/index.shtml* (accessed September 26, 2007)

A

Statement of Task

At the request of the National Science Foundation Engineering Division, the National Academies' Board on Chemical Sciences and Technology will perform an international benchmarking exercise to determine the standing of the U.S. research enterprise relative to its international peers in the field of mechanical engineering. The benchmarking exercise will address the following:

- What is the position of U.S. research in mechanical engineering relative to that in other regions or countries?
- What are the key factors influencing relative U.S. performance in mechanical engineering (i.e., human resources, equipment, infrastructure)?
- On the basis of current trends in the United States and worldwide, extrapolate to the U.S. relative position in the near and longer-term future.

B

Panel Biographical Information

Ward O. Winer (NAE), *Chair*, is the Eugene C. Gwaltney, Jr., Chair of the George W. Woodruff School of Mechanical Engineering at Georgia Institute of Technology. He has responsibilities for programs not only in ME but also in nuclear engineering and medical physics. Dr. Winer's research interests include tribology (friction, lubrication, and wear), thermal systems (heat transfer and fluid mechanics), high-pressure rheology (mechanical behavior of lubricants to pressures of 3 gigapascals), and mechanical system diagnostics (development of instrumentation and methodology for predicting incipient failure in mechanical systems).

Cristina H. Amon (NAE) is dean of the Faculty of Applied Science and Engineering and Alumni Professor in Mechanical and Industrial Engineering at the University of Toronto, Canada, which she joined in 2006. Previously, Amon was the Raymond J. Lane Distinguished Professor of Mechanical and Biomedical Engineering, and director of the Institute for Complex Engineered Systems at Carnegie Mellon University. She received a mechanical engineering degree from Simon Bolivar University in 1981 and, after two years of teaching and engineering practice, continued her education at the Massachusetts Institute of Technology where she earned her M.S. and Sc.D. degrees in 1985 and 1988, respectively. Professor Amon’s research pioneered the development of computational fluid dynamics for formulating and solving thermal design problems subject to multidisciplinary competing constraints. More recently, her research group has been focused on developing numerical algorithms for submicron- and nanoscale heat transport in semiconductors (molecular dynamics, lattice-Boltzmann method, and phonon Boltzmann transport).

L. Catherine Brinson is currently the Jerome B. Cohen Professor of Engineering at Northwestern University and associate chair of the Mechanical Engineering Department with a secondary appointment in the Materials Science and Engineering Department. After receiving her Ph.D. in 1990 from the California Institute of Technology, Dr. Brinson performed postdoctoral studies in Germany at the DLR (German Air and Space Agency), and since 1992 she has been on the faculty at Northwestern University. She focuses on the modeling and characterization of advanced material systems, including high-performance composites and intelligent materials. Current research investigations involve studies of aging in polymeric-based systems, nanomechanics of nanoreinforced polymers, characterization of microporous materials for bone implants, and experiments and modeling of shape memory alloys, where investigations span molecular interactions, micromechanics, and macroscale behavior.

Earl H. Dowell (NAE) is the William Holland Hall Professor of Mechanical Engineering and Materials Science at Duke University. Professor Dowell's research interests are dynamics, fluid and solid mechanics, and acoustics. A particular focus at present is on the dynamics of nonlinear fluid and structural systems and their associated limit cycle and chaotic motions. Examples include flexible plates and shells excited by dynamic fluid forces, oscillating airfoils and wings in a transonic flow, and aeromechanical instability of rotorcraft systems. Also of interest are studies of systems with many degrees of freedom. Dr. Dowell received his B.S. in aeronautics and astronautics from the University of Illinois at

Urbana-Champaign, and his M.S. and Ph.D. in aeronautics and astronautics from the Massachusetts Institute of Technology.

John R. Howell (NAE) is the Ernest Cockrell, Jr., Memorial Chair and Baker Hughes Incorporated Centennial Professor in the Department of Mechanical Engineering at the University of Texas at Austin. He has served on the College of Engineering faculty since 1978 and previously taught at the University of Houston. Dr. Howell received his B.S. and M.S. in chemical engineering and his Ph.D. in engineering from the Case Institute of Technology. His research centers on radiation heat transfer and inverse solutions of combined-mode heat transfer. He is a foreign member of the Russian Academy of Science.

Marshall G. Jones (NAE) is presently a project leader in laser technology at General Electric Corporate Research and Development, which he joined in 1974. Dr. Jones holds 37 U.S. Patents. In 1994, Dr. Jones received the Black Engineer of the Year Award for Outstanding Technical Contribution in Industry and was elected a fellow of the American Society of Mechanical Engineers (ASME). In 1999, Dr. Jones received the National Society of Black Engineers Pioneer of the Year Golden Torch Award. In 2000, he received the Black Engineer of the Year Award for Outstanding Alumnus Achievement. Dr. Jones earned his B.S. in mechanical engineering from the University of Michigan in 1965. He earned his M.S. in 1972 and his Ph.D. in 1974 in mechanical engineering from the University of Massachusetts. He received an honorary doctor of science from the State University of New York in 1985.

Chang-Jin "CJ" Kim is a professor in the Mechanical and Aerospace Engineering Department at the University of California, Los Angeles. His research is in microelectromechanical systems and nanotechnology (MEMS/Nano), including design and fabrication of Micro/Nano structures, actuators, and systems, with a focus on the use of surface tension. Upon joining the faculty at UCLA in 1993, he developed several MEMS courses and established a MEMS Ph.D. major field. He is currently the director of the Micro and Nano Manufacturing Laboratory and a subject editor for the Institute of Electrical and Electronics Engineers-American Society of Mechanical Engineers (IEEE/ASME) *Journal of Microelectromechanical Systems*. Dr. Kim is the recipient of the 1995 TRW Outstanding Young Teacher Award, the 1997 National Science Foundation CAREER Award, and the 2002 Association for Laboratory Automation Achievement Award. He received his Ph.D. in mechanical engineering from the University of California, Berkeley.

Kemper E. Lewis is professor of competitive product and process design in the Department of Mechanical and Aerospace Engineering and executive director of the New York State Center for Engineering Design and Industrial Innovation (NYSCEDII) at the University at Buffalo-State University of New York. His technical interests include large-scale systems design, decentralized design, decision theory, strategic product optimization, and the role of information technology in systems design and development. He received his B.S. in mechanical engineering and B.A. in mathematics from Duke University and his M.S. and Ph.D. degrees in mechanical engineering from the Georgia Institute of Technology, he is the recipient of numerous research and education awards.

Van C. Mow (NAE/IOM) is a Stanley Dicker Professor of Biomedical Engineering and chairman of the Department of Biomedical Engineering at Columbia University. Dr. Mow was elected to the National Academy of Engineering (NAE) in 1991 and Institute of Medicine (IOM) in 1998 for major contributions to orthopedic engineering, particularly understanding the physical behavior of cartilage and the arthritic process. He earned his Ph.D. in applied mechanics from Rensselaer Polytechnic Institute. Dr. Mow has served on numerous professional committees, such as the Steering Committee of the World Association for Chinese Biomedical Engineers, and as well as several NAE and IOM committees. In 2004, the American Society of Mechanical Engineers honored Dr. Mow by establishing the Van C. Mow Medal for Excellence in Bioengineering.

J. Tinsley Oden (NAE) was the founding director of the Institute for Computational Engineering and Sciences (ICES), which was created in January of 2003 as an expansion of the Texas Institute for Computational and Applied Mathematics, also directed by Oden for more than a decade. The institute supports broad interdisciplinary research and academic programs in computational engineering and sciences, involving four colleges and 17 academic departments within the University of Texas at Austin. Dr. Oden received his B.S. in civil engineering from Louisiana State University and Agricultural and Mechanical College, his M.S. in structural engineering from Oklahoma State, and his Ph.D. in engineering mechanics from Oklahoma State. Dr. Oden has also received honorary doctoral degrees from universities in Portugal, Belgium, Poland, and France.

Masayoshi Tomizuka is the Cheryl and John Neerhout, Jr., Distinguished Professor of Mechanical Engineering at the University of California, Berkeley and is a former program director for the Dynamic Systems and Control Program/Civil and Mechanical Systems Division of the National Science Foundation. Dr. Tomizuka's research covers control theory and its applications to various mechanical systems, adaptive control, computer-aided manufacturing, control systems and theory, digital control, dynamic systems, manufacturing, and mechanical vibrations. Dr. Tomizuka received his B.S. and M.S. degrees from Keio University in Japan and his Ph.D. from the Massachusetts Institute of Technology.

C

Journal Analysis

TABLE C-1 List of Journals Examined for Publications and Citations According to Area of Mechanical Engineering

	2006 Impact Factor[a]	Journal Country
GENERAL		
ASME Journal of Applied Mechanics	0.943	US
ACOUSTICS AND DYNAMICS		
ASME Journal of Vibration and Acoustics	0.565	US
Journal of Sound and Vibration	0.884	US
ASA Journal of the Acoustical Society	1.433	US
Journal of Fluids and Structures	0.674	UK
BIOENGINEERING		
Journal of Biomechanics	2.542	UK
ASME Journal of Biomechanical Engineering	1.309	US
Biorheology	2.651	Netherlands
Annals of Biomedical Engineering	2.276	Netherlands
Biomaterials	5.196	UK
Journal of Biomedical Materials Research (A-2.497; B-1.778)	3.652	US
IEEE Transactions of Biomedical Engineering	2.302	US
Journal of Orthopaedic Research	2.784	UK
COMPUTATIONAL MECHANICS		
Computer Methods in Applied Mechanics and Engineering	2.015	Netherlands
Archives of Computational Methods in Engineering	0.800	UK
Computers and Structures	0.846	UK
Computers and Fluids	1.468	UK
International Journal for Numerical Methods in Engineering	1.497	UK
International Journal for Numerical Methods in Fluids	0.870	UK
Communications in Numerical Methods in Engineering	0.518	UK

DESIGN/CAD

ASME Journal of Mechanical Design	1.252	US
ASME Journal of Computing and Information Science in Engineering	0.531	US
Research in Engineering Design	0.667	Germany
Design Studies	N/A	UK
Engineering Optimization	0.557	UK
Journal of Engineering Design	0.955	UK
Computer Aided Design	1.446	UK

DYNAMIC SYSTEMS AND CONTROLS

Automatica	2.273	US
ASME Journal of Dynamic Systems, Measurement and Control	0.658	US
Control Engineering Practice	0.797	UK
IEEE-ASME Transactions on Mechatronics	0.979	US
IEEE Transactions on Control Systems Technology	1.211	US
IEEE Transactions on Automatic Control	2.772	US
IEEE Transactions on Robotics and Automation	0.652	US

ENERGY SYSTEMS

Solar Energy	1.431	US
ASME Journal of Solar Energy Engineering	0.421	US
Journal of Power Sources	3.521	Netherlands
ASME Journal of Energy Resources Technology	0.370	US
Nuclear Engineering and Design	0.461	Switzerland
Nuclear Technology	0.537	US
Nuclear Science and Engineering	0.578	US

MANUFACTURING/CAM

ASME Journal of Manufacturing Science and Engineering	0.536	US
IEEE Transactions on Advanced Packaging	1.443	US
International Journal of Machine Tools and Manufacture	1.184	UK
Journal of Manufacturing Systems (SME)	0.150	US
IEEE Transactions on Components and Packaging Technologies	0.816	US

MECHANICS OF ENGINEERING MATERIALS

Journal of the Mechanics and Physics of Solids	3.609	US
Mechanics of Materials	2.106	Netherlands
Advanced Materials	7.896	US
ASME Journal of Engineering Materials and Technology		US

MEMS/Nano		
Journal of Micromechanics and Microengineering	2.321	UK
IEEE/ASME Journal of Microelectromechanical Systems	2.659	US
THERMAL SYSTEMS AND HEAT TRANSFER		
International Journal of Heat and Mass Transfer	1.482	UK
Journal of Heat Transfer-Transaction of ASME	0.886	US
Combustion and Flame	1.828	US
Journal of Electronic Packaging	0.487	US
Physics of Fluids	1.697	US
ASME Journal of Fluids Engineering	0.678	US
Journal of Fluid Mechanics	2.022	Germany
International Communications in Heat and Mass Transfer	0.708	UK
Numerical Heat Transfer Part A (0.936) and B(0.913) (impact factor averaged)	0.925	US
Experimental Heat Transfer	0.361	US
TRIBOLOGY		
Journal of Tribology-Transactions of ASME	0.810	US
Tribology Transactions	0.507	US
Wear	1.180	UK
Tribology International	1.132	UK
Tribology Letters	1.090	US

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[a] SOURCE: 2006 Journal Citation Reports®. Reprinted with permission from Thomson Scientific.

[b] *IEEE Transactions on Robotics and Automation* split into two new titles in 2004: *IEEE Transactions on Robotics* and *IEEE Transactions on Automation Science and Engineering*.

TABLE C-2 U.S. Journal Article Contributions[a]

	1999			2003			2005		
	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.
GENERAL									
ASME Journal of Applied Mechanics	157	66	42	127	65	51	129	74	57
ACOUSTICS AND DYNAMICS									
ASME Journal of Vibration and Acoustics	79	29	37	71	34	48	70	40	57
Journal of Sound and Vibration	522	113	22	756	136	18	663	177	27
ASA Journal of the Acoustical Society	670	340	51	556	310	56	688	359	52
Journal of Fluids and Structures	55	14	25	118	36	31	107	28	26
Area Average			34			38			41
BIOENGINEERING									
Journal of Biomechanics	171	65	38	217	96	44	269	125	46
ASME Journal of Biomechanical Engineering	89	70	79	112	71	63	144	101	70
Biorheology	24	7	29	22	10	45	22	10	45
Annals of Biomedical Engineering	79	62	78	134	89	66	166	115	69
Biomaterials	261	76	29	260	55	21	260	51	20
Journal of Biomedical Materials Research	353	151	43	511	207	41	502	184	37
IEEE Transactions on Biomedical Engineering	172	89	52	137	61	45	244	124	51
Journal of Orthopaedic Research	129	85	66	155	87	56	195	101	52
Area Average			52			48			49

	1999			2003			2005		
	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.
COMPUTATIONAL MECHANICS									
Computer Methods in Applied Mechanics and Engineering	297	100	34	233	66	28	241	78	32
Archives of Computational Methods in Engineering	8	4	50	3	2	67	8	3	38
Computers and Structures	193	32	17	235	48	20	208	42	20
Computers and Fluids	39	17	44	44	14	32	55	15	27
International Journal for Numerical Methods in Engineering	275	86	31	296	103	35	266	82	31
International Journal for Numerical Methods in Fluids	178	42	24	192	44	23	238	53	22
Communications in Numerical Methods in Engineering	83	17	20	81	16	20	64	16	25
Area Average			31			32			28
DESIGN/CAD									
ASME Journal of Mechanical Design	95	50	53	102	50	49	150	78	52
ASME Journal of Computing and Information Science in Engineering	—	—	—	44	25	57	45	20	44
Computer-Aided Design	66	28	42	106	30	28	112	32	29
Research in Engineering Design	17	11	65	20	6	30	15	7	47
Design Studies	31	6	19	30	7	23	27	6	22
Engineering Optimization	41	16	39	42	6	14	48	10	21
Area Average			44			34			36

	1999			2003			2005		
	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.
DYNAMIC SYSTEMS AND CONTROLS									
Automatica (IFAC Journal)	191	52	27	216	63	29	223	52	23
ASME Journal of Dynamic Systems, Measurement and Control	113	57	50	96	44	46	84	44	52
Control Engineering Practice	131	9	7	128	25	20	130	14	11
IEEE-ASME Transactions on Mechatronics	44	19	43	54	24	44	82	30	37
IEEE Transactions on Control Systems Technology	74	36	49	95	40	42	116	56	48
IEEE Transactions on Automatic Control	364	143	39	307	136	44	264	96	36
IEEE Transactions on Robotics and Automation	106	52	49	97	43	44	163	72	44
Area Average			38			39			36
ENERGY SYSTEMS									
Solar Energy	107	7	7	98	13	13	153	16	10
ASME Journal of Solar Energy Engineering	33	12	36	76	54	71	77	33	43
Journal of Power Sources	391	72	18	591	167	28	710	144	20
ASME Journal of Energy Resources Technology	45	34	76	39	17	44	41	22	54
Nuclear Engineering and Design	208	37	18	173	14	8	191	23	12
Nuclear Technology	114	38	33	111	38	34	114	42	37
Nuclear Science and Engineering	80	37	46	80	29	36	87	41	47
Area Average			33			34			32

	1999			2003			2005		
	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.
MANUFACTURING/CAM									
ASME Journal of Manufacturing Science and Engineering	106	70	66	99	70	71	103	63	61
IEEE Transactions on Advanced Packaging	80	50	63	56	38	68	79	46	58
International Journal of Machine Tools and Manufacture	117	32	27	161	40	25	174	36	21
Journal of Manufacturing Systems (SME)	22	12	55	25	15	60	19	11	58
IEEE Transactions on Components and Packaging Technologies	74	37	50	84	53	63	101	59	58
Area Average			52			57			51
MECHANICS OF ENGINEERING MATERIALS									
Journal of the Mechanics and Physics of Solids	91	43	47	99	67	68	113	64	57
Mechanics of Materials	55	27	49	78	44	56	83	35	42
Advanced Materials	297	84	28	473	162	34	584	215	37
ASME Journal of Engineering Materials and Technology	72	44	61	58	27	47	60	34	57
Area Average			46			51			48

	1999			2003			2005		
	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.
MEMS-NANO									
Journal of Micromechanics and Microengineering	71	11	15	154	32	21	353	106	30
IEEE/ASME Journal of Microelectromechanical Systems	63	46	73	107	78	73	146	102	70
Area Average			44			47			50
THERMAL SYSTEMS AND HEAT TRANSFER									
International Journal of Heat and Mass Transfer	299	89	30	429	114	27	463	136	29
ASME Journal of Heat Transfer	155	88	57	149	85	57	176	104	59
Combustion and Flame	179	81	45	186	68	37	155	66	43
Journal of Electronic Packaging	46	35	76	89	38	43	73	27	37
Physics of Fluids	378	203	54	383	172	45	604	259	43
ASME Journal of Fluids Engineering	119	38	32	128	59	46	140	56	40
Journal of Fluid Mechanics	337	170	50	379	169	45	401	188	47
International Communications in Heat and Mass Transfer	117	25	21	114	12	11	147	22	15
Numerical Heat Transfer PART A and B (Impact Factor averaged)	142	54	38	148	45	30	160	46	29
Experimental Heat Transfer	22	5	23	17	5	29	19	4	21
Area Average			43			37			36

	1999			2003			2005		
	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.	Total articles	U.S. author address	% U.S.
TRIBOLOGY									
ASME Journal of Tribology	138	56	41	108	52	48	110	47	43
Tribology Transactions	120	57	48	78	37	47	71	26	37
Wear	388	74	19	315	54	17	392	62	16
Tribology International	80	8	10	123	20	16	122	31	25
Tribology Letters	57	34	60	87	26	30	131	57	44
Area Average			35			32			33
TOTAL MECHANICAL ENGINEERING			**41**			**41**			**40**

[a] See summary in Figure 3-3.

TABLE C-3 U.S. Contributions to 50 Most-Cited Articles in Select Mechanical Engineering Journals

	1995		1997		1999		2001		2003		2005	
	U.S. Author Address	U.S. %	U.S. Author Address	U.S. %	U.S. Author Address	U.S. %	U.S. Author Address	U.S. %	U.S. Author Address	U.S. %	U.S. Author Address	U.S. %
ASME Journal of Applied Mechanics	27	54	25	50	18	36	35	70	29	58	30	60
Journal of Sound and Vibration	24	48	18	36	10	20	10	20	14	28	22	44
Biomaterials	10	20	15	30	22	44	17	34	19	38	12	24
International Journal for Numerical Methods in Engineering	19	38	26	52	29	58	20	40	24	48	23	46
Computer Aided Design	27	54	34	68	23	46	23	46	14	28	17	34
IEEE Transactions on Robotics and Automation	27	54	23	46	19	38	17	34	24	48	20	34
Journal of Power Sources	11	22	7	14	10	20	9	18	18	36	11	22
ASME Journal of Manufacturing Science and Engineering			41	82	35	66	37	73	42	71	36	69
Journal of the Mechanics and Physics of Solids	22	61	32	64	30	60	36	72	36	72	32	64
IEEE/ASME Journal of Microelectromechanical Systems	6	60	16	80	25	83	22	73	39	78	35	70
ASME Journal of Fluids Engineering	32	64	25	50	21	42	20	40	25	50	23	46
Wear	13	26	17	34	7	14	6	12	11	22	17	34
Journal average	20	46	23	51	21	44	21	44	25	48	23	43

NOTE: IEEE Transactions on Robotics and Automation split into two new titles in 2004: *IEEE Transactions on Robotics* and *IEEE Transactions on Automation Science & Engineering*.

D

Virtual World Congress

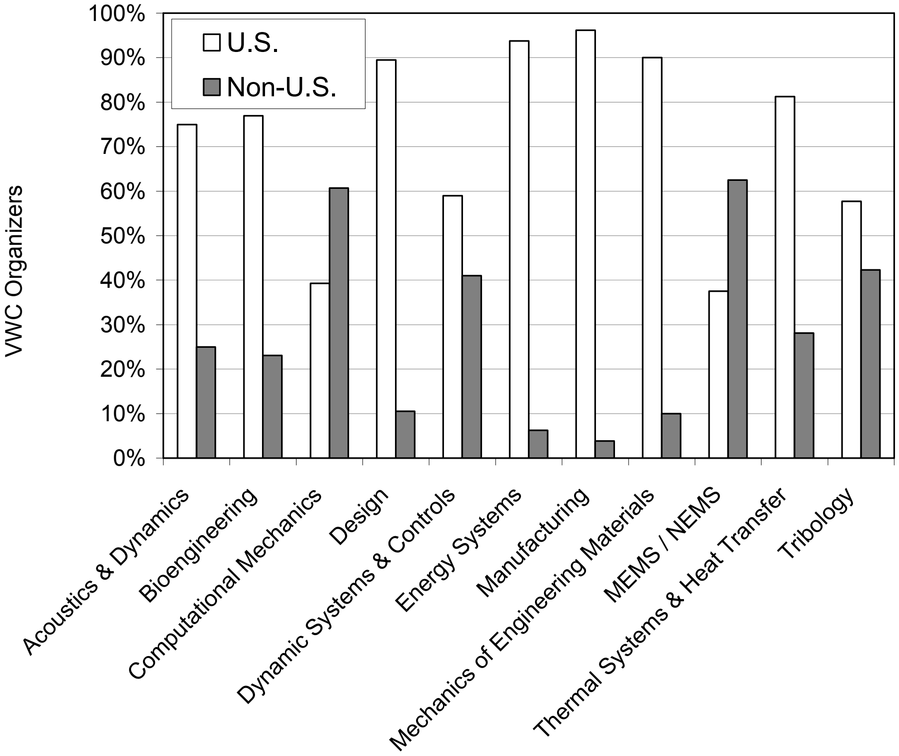

FIGURE D-1 Summary of the percentage of U.S. or non-U.S. virtual world congress organizers by area of mechanical engineering.

TABLE D-1 Detailed Results for Mechanical Engineering Virtual World Congress

		Organizers				**Speakers**				**Speakers by U.S. Organizers**				**Speakers by Non-U.S. Organizers**			
Area	**SubArea**	**No. of Organizers**	**U.S.**	**Non-U.S.**	**%U.S.**	**No. of Speakers**	**U.S.**	**Non-U.S.**	**%U.S.**	**No. of Speakers**	**U.S.**	**Non-U.S.**	**%U.S.**	**No. of Speakers**	**U.S.**	**Non-U.S.**	**%U.S.**
Acoustics and Dynamics	Acoustics	6	6	0	100	109	45	64	41	109	45	64	41				
	Dynamics	10	6	4	60	194	116	78	60	123	85	38	69	71	31	40	44
	Subarea Total	*16*	*12*	*4*	*75*	*303*	*161*	*142*	*53*	*232*	*130*	*102*	*56*	*71*	*31*	*40*	*44*
Bioengineering	Biomechanics	4	4	0	100	57	45	12	79	60	46	14	77	60	46	14	77
	Constitutive modeling	3	2	1	67	58	37	21	64								
	Molecular and cellular biomechanics	2	2	0	100	20	15	5	75	20	15	5	75				
	Functional tissue engineering	2	1	1	50	39	34	5	87								
	Biomaterials	2	1	1	50	20	15	5	75	20	15	5	75				
	Subarea Total	*13*	*10*	*3*	*77*	*194*	*146*	*48*	*75*	*100*	*76*	*24*	*76*	*60*	*46*	*14*	*77*
Computational Mechanics																	
	Computational engineering science and design[a]	6	3	3	50	113	50	63	44	53	30	23	57	60	20	40	33
	Computational fluid dynamics	5	2	3	40	88	42	46	48	40	22	18	55	48	20	28	42
	Computational solid mechanics	17	6	11	35	288	149	139	52	82	55	27	67	206	94	112	46
	Subarea Total	*28*	*11*	*17*	*39*	*489*	*241*	*248*	*49*	*175*	*107*	*68*	*61*	*314*	*134*	*180*	*43*
Design																	
	Design informatics and environments	8	8	0	100	104	88	16	85	104	88	15	85				
	Design simulation and modeling	10	9	1	90	141	126	15	89	129	116	13	90	12	10	2	83
	Design theory	11	9	2	82	156	115	41	74	128	102	26	80	28	13	15	46
	Design synthesis	9	8	1	89	131	90	41	69	114	81	33	71	17	9	8	53
	Subarea Total	*38*	*34*	*4*	*89*	*532*	*419*	*113*	*79*	*475*	*387*	*87*	*81*	*57*	*32*	*25*	*56*
Dynamic Systems and Controls	Control system design methodologies: Control theories	8	6	2	75	151	91	60	60	111	74	37	67	40	23	40	58
	Enabling technologies	6	6	0	100	104	56	48	54	104	56	48	54				
	Mechatronics and applications	11	4	7	36	197	79	118	40	73	49	24	67	124	30	94	24
	Modeling, identification and simulation	6	3	3	50	112	42	70	38	51	24	27	47	61	18	43	30
	Robotics and automation	8	4	4	50	150	82	68	55	79	52	27	66	71	30	41	42
	Subarea Total	*39*	*23*	*16*	*59*	*714*	*350*	*364*	*49*	*418*	*255*	*163*	*61*	*296*	*101*	*218*	*34*
Energy Systems	Energy conversion and storage (combined)	5	4	1	80	74	42	37	57	62	34	28	55	12	3	9	25
	Nuclear energy	7	7	0	100	134	104	30	78	134	104	30	78				
	Renewable energy systems and sources	4	4	0	100	66	39	27	59	66	39	27	59				
	Subarea Total	*16*	*15*	*1*	*94*	*274*	*185*	*94*	*68*	*262*	*177*	*85*	*68*	*12*	*3*	*9*	*25*

		Organizers				**Speakers**				**Speakers by U.S. Organizers**				**Speakers by Non-U.S. Organizers**			
Area	**SubArea**	**No. of Organizers**	**U.S.**	**Non-U.S.**	**%U.S.**	**No. of Speakers**	**U.S.**	**Non-U.S.**	**%U.S.**	**No. of Speakers**	**U.S.**	**Non-U.S.**	**%U.S.**	**No. of Speakers**	**U.S.**	**Non-U.S.**	**%U.S.**
Manufacturing	Toolings and equipment	5	5	0	100	83	41	42	49	83	41	42	49				
	Metrology	4	4	0	100	66	28	38	42	66	28	38	42				
	processes	8	7	1	88	129	76	53	59	118	74	44	63	11	2	9	18
	Systems	4	4	0	100	58	30	28	52	58	30	28	52				
	Quality	5	5	0	100	53	31	22	58	53	31	22	58				
	Subarea Total	*26*	*25*	*1*	*96*	*389*	*206*	*183*	*53*	*378*	*204*	*174*	*54*	*11*	*2*	*9*	*18*
Mechanics of Engineering Materials	Durability mechanics	8	7	1	88	129	86	43	67	109	74	35	68	20	12	8	60
	Experimental mechanics	6	6	0	100	110	91	19	83	110	91	19	83				
	Multiscale mechanics and computational materials	10	8	2	80	154	112	42	73	128	96	32	75	26	16	10	62
	Nano-mechanics and nanomaterials	6	6	0	100	121	100	21	83	121	100	21	83				
	Subarea Total	*30*	*27*	*3*	*90*	*514*	*389*	*125*	*76*	*468*	*361*	*107*	*77*	*46*	*28*	*18*	*61*
MEMS / NEMS		8	3	5	38	83	47	36	57	29	8	29	28	54	26	28	48
Thermal Systems & Heat Transfer	Applications	10	8	2	80	194	124	70	64	157	105	52	67	37	19	18	51
	Combustion	5	5	0	100	87	49	38	56	87	49	38	56				
	Fluid mechanics	5	3	5	60	77	47	30	61	31	28	3	90	46	19	27	41
	Heat transfer	7	5	2	71	122	86	36	70	90	70	20	78	32	16	16	50
	Nano/Micro systems	5	5	0	100	82	61	21	74	82	61	21	74				
	Subarea Total	*32*	*26*	*9*	*81*	*562*	*367*	*195*	*65*	*447*	*313*	*134*	*70*	*115*	*54*	*61*	*47*
Tribology	Contact mechanics and surface engineering	6	5	1	83	128	68	60	53	101	54	47	53	27	14	13	52
	Diagnositcs of tribosystems	3	0	3	0	54	20	34	37					54	20	34	37
	Friction and wear	4	2	2	50	67	31	36	46	28	16	12	57	39	15	24	38
	Hydrodynamic phenomena	8	4	4	50	135	61	74	45	64	41	23	64	71	20	51	28
	Tribomaterials	5	4	1	80	87	45	42	52	74	41	33	55	13	4	9	31
	Subarea Total	*26*	*15*	*11*	*58*	*471*	*225*	*246*	*48*	*267*	*152*	*115*	*57*	*204*	*73*	*131*	*36*
TOTAL		**272**	**201**	**74**	**74**	**4,525**	**2,736**	**1,794**	**60**	**3,251**	**2,170**	**1,088**	**67**	**1,240**	**530**	**733**	**43**

NOTE: [a] combination of computational metods in design and optimization, and electromechanical systems, computational bioengineering, and computational electromagnetics

Table D-2 List of Experts Who Nominated Keynote Speakers for the Virtual World Congresses (Virtual Congress Organizers)

Last	First	Affiliation
Achenbach	Jan	Northwestern, Evanston, Illinois
Adams	George G.	Northeastern University, Boston, Massachusetts
Adams	Marvin	Texas A&M, College Station, Texas
Agonafer	Dereje	University of Texas, Arlington
Allen	Janet K.	Georgia Institute of Technology, Atlanta
Ammannati	Fabio G.	Italy
Antsaklis	Panos	University of Notre Dame, Notre Dame, Indiana
Arimoto	Suguru	Ritsumeikan University, Kyoto, Japan
Arruda	Ellen M.	University of Michigan, Ann Arbor
Asada	H. Harry	Massachusetts of Technology, Cambridge
Aubry	Nadine	New Jersey Institute of Technology, Newark
Auslander	Dave	University of California, Berkeley,
Ayyaswamy	P.S.	University of Pennsylvania, Philadelphia
Bao	Greg	Georgia Institute of Technology, Atlanta
Bar-Cohen	Avram	University of Maryland, College Park
Barlow	Robert S.	Sandia National Laboratory, Livermore, Calififornia
Bathe	Klaus-Jurgen	Massachusetts Institute of Technology, Cambridge
Baum	Howard	National Institute of Standards and Technology, Gaithersburg, Maryland
Bazant	Zdenek	Northwestern University, Evanston, Illinois
Bejan	Adrian	Duke University, Durham, North Carolina
Belytschko	Ted	Northwestern University, Evanston, Illinois
Bendsoe	Martin P.	Technical University of Denmark, Lyngby, Denmark
Bergles	Arthur E.	Massachusetts Institute of Technology, Cambridge
Bettig	Bernhard	Michigan Technological University, Houghton
Bhushan	Bharat	Ohio State, Columbus
Blanchet	Thierry	Rensselaer Polytechnic Institute, Troy, New York
Blau	Peter	Oak Ridge National Laboratory, Oak Ridge, Tennessee
Book	Wayne J.	Georgia Institute of Technology, Atlanta
Boothroyd	Geoffrey	University of Rhode Island, Kingston
Cahill	David	University of Illinois, Urbana-Champagne
Campbell	Matthew	University of Texas, Austin
Carpick	Robert W.	University of Wisconsin, Madison
Castaneda	Pedeo Ponte	University of Pennsylvania, Philadelphia
Chang	Fu-Kuo	Stanford University, Stanford, California
Chen	Gang	Massachusetts Institute of Technology, Cambridge
Chen	Wei	Northwestern University, Evanston, Illinois
Cho	H.S.	Korea

Last	First	Affiliation
Cho	Young-Ho	Korea Advanced Institute of Science and Technology
Cho Chew	Weng	University of Illinois, Urbana-Champagne
Clemens	Noel	University of Texas, Austin
Cocks	Alan	University of Oxford, Leicester, United Kingdom
Corrandini	Michael	University of Wisconsin, Madison
Crocker	Malcolm J.	Auburn University, Auburn, Alabama
Curtin	Bill	Brown University, Providence, Rhode Island
Daniel	Isaac	Northwestern University, Evanston, Illinois
Danyluk	Steven	Georgia Institute of Technology, Atlanta
de Borst	Rene	Delft University, Delft, Netherlands
de Vahl		
Davis	Graham	University of South Wales, Kensington, Australia
de Weck	Olivier	Massachusetts Institute of Technology, Cambridge
Demkowicz	Leszek	University of Texas, Austin
DeVor	Richard	University of Illinois, Urbana
Diaz	Nils	Nuclear Regulatory Ccommission, Washington, District of Columbia
Diaz	Alejandro	Michigan State University, East Lansing
Dong	Cheng	Pennsylvania State University, University Park
Donmez	Alkan	National Institute of Standards and Technology, Gaithersburg, Maryland
Dopazo	Cesar	University of Zaragoza, Spain
Dornfeld	David A.	University of California, Berkeley
Dowling	David	University of Michigan, Ann Arbor
Downar	Tom	Purdue University, West Lafayette, Indiana
Du	Xiaoping	University of Missouri, Rolla
Dubowsky	Steve	Massachusetts Institute of Technology, Cambridge
Dwyer-Joyce	R.	University of Sheffield, United Kingdom
Dynn	Clive L.	Harvey Mudd College, Claremont, California
Eijk	Jon Von	Delft University of Technology, Netherlands
Elwenspaek	M. C. (Miko)	University of Twente, Enschede, Netherlands
Epureanu	Bogdan	University of Michigan, Ann Arbor,
Erdemer	Ali	Argonne National Laboratory, Illinois
Espinosa	Horacio D.	Northwestern, Evanston, Illinois
Estler	Tyler	National Institute of Standards and Technology, Gaithersburg, Maryland
Ethier	C. Ross	University of Toronto, Canada
Etsion	Izhak	University of California, San Diego
Fadel	Georges	Clemson University, South Carolina
Farassat	F.	National Air and Space Administration, Langley, Maryland
Farhat	Charbel	Stanford University, California

Last	First	Affiliation
Flannery	Hunter	National Institute of Standards and Technology, Gaithersburg, Maryland
Frecker	Mary	Pennsylvania State University, University Park
Freund	L. B.	Brown University, Providence, Rhode Island
Frey	Dan	Massachusetts Institute of Technology, Cambridge
Fukuda	Toshio	Nagoya University, Japan
Furuta	Katsuhsia	Tokoy Denki University, Japan
Gao	Huajian	Brown University, Providence, Rhode Island
Gardner	Martha	General Electric
Garimella	Sureh	Purdue University, West Lafayette, Indiana
Gates	Thomas S.	National Air and Space Administration, Langley, Maryland
Ge	Christine Ping	Oregon State University, Corvallis
Gero	John S.	University of Sydney, Australia
Gershenson	John K.	Michigan Technological University, Houghton
Ghattas	Omar	University of Texas, Austin
Ghoniem	Ahmed	Massachusetts Institute of Technology, Cambridge
Gigoropoulos	Costas P.	University of California, Berkeley
Giurgiutiu	Victor	University of South Carolina, Columbia
Goodenough	John	University of Texas, Austin
Goodwin	Graham C.	University of Newcastle, New South Wales, Australia
Goswami	Yogi	University of South Florida, Gainesville
Gu	WY	University of Miami, Coral Gables, Florida
Guilak	Farshid	Duke University, Durham, North Carolina
Guo	X.Ed	Columbia University, New York
Gupta	Satyandra K.	University of Maryland, College Park
Guzzella	Lino	Swiss Federal Institute of Technology, Zurich
Habashi	Wagdi G. (Fred)	McGill University, Montreal, Canada
Haftka	Raphael T.	University of Florida, Gainesville
Han	Je-Chin	TexasA&M University, College Station
Hara	Shinji	University of Tokyo, Bunkyo, Tokyo, Japan
Harding	Kevin	GE Global
Hendrick	Karl	University of California, Berkeley
Herzog	Walter	University of Calgary, Alberta, Canada
Hirizinger	Gerd	Institute of Robotics and Mechatronics, Germany
Ho	Chih-Ming	University of California, Los Angeles
Hocken	Robert	University of North Carolina, Charlotte
Holm	Elizabeth A.	Sandia National Laboratory, Livermore, California
Holmberg	Kenneth	VTT, Finland

Last	First	Affiliation
Holmes	Philip	Princeton University, Princeton, New Jersey
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