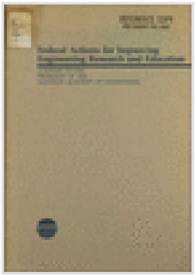

Federal Actions for Improving Engineering Research and Education: A Report to the President of the National Academy of Engineering (1986)

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FEDERAL ACTIONS FOR IMPROVING ENGINEERING RESEARCH AND EDUCATION

A Report to the President of the National Academy of Engineering

**Prepared by
The Committee to Identify Critical Issues in Federal Support for Engineering and Technology**

**National Academy of Engineering
Washington, D.C. 1986**

The National Academy of Engineering is a private organisation established in 1964. It shares in the responsibility given the National Academy of Sciences under a congressional charter granted in 1863 to advise the federal government on questions of science and technology. The collaboration is implemented primarily through the National Research Council. The National Academy of Engineering also recognises distinguished engineers, sponsors engineering programs aimed at meeting national needs, and encourages education and research.

The members of the committee responsible for the report are drawn from the National Academy of Engineering and were chosen for their special competences and with regard for appropriate balance. This report has been reviewed by members of the National Academy of Engineering other than the authors.

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Office of the President

June 4, 1986

The Honorable Don Fuqua
Chairman, Science Policy Task Force
Chairman, Committee on Science
and Technology
U.S. House of Representatives
2269 Rayburn House Office Building
Washington, DC 20515

Dear Mr. Fuqua:

At the May 6, 1986 hearing of the House of Representatives Science Policy Task Force, I offered to submit for the record a report by a Committee of members of this Academy entitled "Federal Actions for Improving Engineering Research and Education." I am pleased to transmit to you and members of the Task Force the enclosed report prepared by the NAE committee to Identify Critical Issues in Federal Support for Engineering and Technology. The Committee was chaired by Cornelius J. Pings, Provost, University of Southern California. A list of Committee members is included in the report.

This report is not a comprehensive review of federal policies that affect engineering research and education. Instead, it highlights certain policies that the Committee believes will provide useful input to the deliberations of the Science Policy Task Force. We look forward to continuing to work with you, the Task Force, and Task Force staff members in your study of this important area of federal policy.

Sincerely,

Robert M. White
President

cc: Cornelius Pings

NATIONAL ACADEMY OF ENGINEERING 2101 CONSTITUTION AVENUE, N.W., WASHINGTON, D.C. 20418

3 June 1986

Dr. Robert M. White
President
National Academy of Engineering
2101 Constitution Avenue, N.W.
Washington, DC 20418

Dear Dr. White:

I am pleased to transmit to you the report of the National Academy of Engineering Committee to Identify Critical Issues in Federal Support for Engineering and Technology. You will recall that the Committee was formed in January of 1986 to prepare a report to the NAE President outlining critical issues relevant to the efforts of the House of Representatives Committee on Science and Technology Task Force on Science Policy. I believe that the attached report represents a reasonable consensus of all members of the NAE Committee and that our report should help ensure that the interests and concerns of the engineering profession are adequately considered by the Task Force.

On behalf of the Committee, let me thank you for the opportunity to share our views with you and the Task Force. We strongly support an active role by the engineering community in considering issues and policies in the federal arena.

Yours truly,

Cornelius J. Pings
Chairman, Committee to Identify Critical Issues in Federal Support for Engineering and Technology

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PREFACE

In 1984 the House of Representatives Science Policy Task Force began an examination of national policy as it relates to the support and function of basic and applied research and to the support of engineering and science education by the federal government. The study is the most comprehensive undertaken since 1944 when Vannevar Bush was commissioned by President Roosevelt to examine the role of science in post-World War II America. After publication of the Bush report, *Science, The Endless Frontier*, there were several congressional reviews of U.S. science policy completed during the early 1960s, prompted partly by the launch of Sputnik in 1957. These reviews were more limited in scope than the Bush report and were related primarily to the perceived Soviet challenge to U.S. leadership in science and technology.

The Science Policy Task Force has focused its study on the performance of basic and applied research and its support by the federal government. In 1985 and 1986 the Task Force held many hearings on the role of the federal government in support of engineering and scientific research. Robert M. White, President, National Academy of Engineering, asked a Committee of NAE members to identify critical issues in federal support for engineering and technology and prepare a report that could serve as a basis for NAE input to the Task Force.

To accomplish this, the NAE Committee to Identify Critical Issues in Federal Support for Engineering and Technology met at the Academy on February 27 and 28, 1986. The Committee benefited from presentations by John Holmfeld, Science Consultant, Subcommittee on Science, Research, and Technology, Committee on Science and Technology, U.S. House of Representatives, and John McTague, Acting Science Advisor to the President and Acting Director, Office of Science and Technology Policy, Executive Office of the President.

This report is not a comprehensive review of federal policies that affect engineering. Such a review might range over topics as diverse as tort law and anti-trust, tax, and procurement policies. Instead, this report highlights issues in federal support for engineering research and education that the Committee believes will provide useful input to the deliberations of the Science Policy Task Force. The recommendations for federal support of engineering made in this report focus largely on academic research and education and their relation to engineering research conducted in industry and federal laboratories. Other recent reports have taken comprehensive looks at engineering education and practice in the United States. The National Research Council Committee on the Education and Utilization of the Engineer published a detailed report on U.S. engineering education and practice (National Research Council, 1985), and a comprehensive report on engineering research is currently being prepared by the National Research Council Engineering Research Board (National Research Council, 1986).

COMMITTEE MEMBERSHIP

National Academy of Engineering Committee to Identify Critical Issues in Federal Support for Engineering and Technology

Cornelius J. Pings (*Chairman*), Provost, University of Southern California

John C. Calhoun, Jr., Deputy Chancellor for Engineering, Emeritus, The Texas A & M University System

George F. Carrier, T. Jefferson Coolidge Professor of Applied Mathematics, Harvard University

Ray W. Clough, Nishkian Professor of Structural Engineering, University of California at Berkeley

W. Dale Compton, NAE Senior Fellow

George C. Dacey, President, Sandia National Laboratories (retired)

Ruth M. Davis, President, Pymatuning Group, Arlington, Virginia

W. Kenneth Davis, Consultant, Bechtel Power Corporation, San Francisco

Milton C. Edlund, Professor of Mechanical and Nuclear Engineering, Virginia Polytechnic Institute and State University

Peter T. Flawn, Vice-Chairman, The Rust Group, Inc., Austin, Texas

Alexander H. Flax, NAE Home Secretary

John E. Flipse, Associate Chancellor and Associate Dean of Engineering, Texas A & M University

Serge Gratch, Director, Vehicle, Powertrain and Component Research Laboratory, Ford Motor Company, Dearborn, Michigan

Noel Jarrett, Technical Director, Chemical Engineering R & D, Alcoa Laboratories, Alcoa Center, Pennsylvania

Thomas D. Larson, Secretary, Pennsylvania Department of Transportation

John P. Longwell, Professor, Department of Chemical Engineering, Massachusetts Institute of Technology

Franklin K. Moore, Joseph C. Ford Professor of Mechanical Engineering, Cornell University

EXECUTIVE SUMMARY

The Committee to Identify Critical Issues in Federal Support for Engineering and Technology reached consensus on the following points:

1. The Need for Commitment to Technological Leadership

We believe that it is time for national policy to emphasize the critical role of engineering—alongside scientific discovery—in building U.S. technological advantage.

Federal support for engineering research and education has contributed significantly to the vigor of U.S. engineering and technology and remains an effective means for strengthening the technological status of the nation. Declining competitiveness currently challenges the global industrial leadership of the United States. Success in addressing this challenge will depend in large part on our nation's ability to reap technological benefits from investment in basic research. Although policies of federal support for engineering research and education have served the nation well, we now need to ask how such policies can provide a stronger framework for ensuring our technological future.

2. Achieving the Appropriate Mix of Research Opportunities

The federal government should pay particular attention to the need for balanced support for the spectrum of research opportunities. The appropriate mix of engineering research funds—from single-investigator awards to cross-disciplinary, multi-investigator projects—will continue to be influenced by social need, technical opportunity, and the demand for specialized facilities. We emphasize that individual-investigator grants are an essential funding instrument in engineering research, and we urge the National Science Foundation and federal mission agencies to continue supporting excellent young engineering faculty members by a variety of mechanisms. We particularly recommend expansion of programs that give special support to young investigators, such as the NSF Presidential Young Investigator (PYI) grant program. We also strongly endorse funding of multi-investigator engineering programs, such as the National Science Foundation Engineering Research Centers and the Department of Defense University Research Initiative. These programs provide disciplinary and cross-disciplinary research opportunities for faculty and students, promote cooperation between universities and industry, and provide new knowledge in key technological areas.

3. Research Collaboration Among Universities, Industry, and Federal Laboratories

Federal agencies can strengthen engineering research by establishing or increasing support for research programs that encourage long-term collaboration and communication between university graduate students and faculties and their counterparts in federal laboratories and industry.

4. Research on Innovative Technologies

To maintain technological leadership, it is necessary not only to make incremental improvements in the current generation of technologies but also to identify and assess new concepts and incipient technologies. We therefore urge federal agencies to consider their roles in enhancing support for innovative technologies.

5. Relevance of Engineering Education to Industrial Competitiveness

The federal government can help increase the relevance of engineering education to the nation's industrial competitiveness. We urge federal agencies to improve incentives and mechanisms for students and faculty members to establish productive ties with peers in industry and mission agencies. In addition, there is a need to recognize the value that industry places on the master's degree in engineering, and we urge that ways be developed to increase the availability and quality of master's degree engineering programs.

6. Shortage of Ph.D.'s

We believe that the present level production of Ph.D.'s in engineering is inadequate to meet future industrial, academic, and governmental needs. A high priority must be to provide essential support to graduate engineering students pursuing the Ph.D. degree.

7. Life-Long Engineering Education

Effective continuing education throughout a career can enable engineers to avoid technological obsolescence and remain productive. The federal government can support the development of a system for life-long engineering education by providing incentives for companies, universities, and individuals to invest in such programs.

8. Shortages of Faculty in Engineering Schools

We agree with the findings of recent reports suggesting that the single most pressing problem in engineering education today is the shortage of faculty members. This shortage limits attempts to increase the quality, scope, and number of engineering programs in universities. The incentive to pursue a university career is often based on the opportunity to carry out engineering research without the tight organizational controls characteristic of industry. Therefore, the federal government can enhance the quality of engineering education in the United States by strongly supporting university-based engineering research.

9. Support for University Equipment and Facilities

The federal government can enhance engineering education by increasing support for instructional and research facilities and equipment at engineering colleges and universities. We recommend that federal agencies expand programs that provide equipment to universities in support of engineering projects. Such programs will help alleviate severe problems of equipment obsolescence and facilities deterioration that plague both engineering and science education at colleges and universities and will assist in recruitment of high-quality faculty members.

10. Stability of Federal Support for Engineering Education and Research

We endorse two recommendations from the recent report of the White House Science Council Panel on the Health of U.S. Universities and Colleges: federal agencies should (1) establish a substantial program of multiyear, merit-based graduate fellowships in engineering and (2) extend the average duration of research grants to three—or preferably five—years.

INTRODUCTION

In 1945, Vannevar Bush, Director of the Office of Scientific Research and Development under President Roosevelt, prepared a report to the President on a program for postwar scientific research (Bush, 1945). In that report, *Science, The Endless Frontier*, Bush urged the federal government to support basic research in colleges, universities, and research institutes. He argued that economic growth, progress against disease, and defense against aggression could be obtained only through a national commitment to federal support for basic scientific research and through new institutional mechanisms organized for that purpose. The Bush report correctly implied that national policy should focus on investment in the research process rather than simply on procurement of research results.

Bush's arguments were well received, and many of his recommendations have been implemented. The National Science Foundation has developed as a principal governmental institution for accomplishing the nation's research objectives. We now accept as a matter of course that much of our nation's economic welfare, national security, and health is directly related to past investments in research and technological development—investments encouraged by the Bush report.

Today we face an unprecedented global challenge to U.S. industrial leadership. This challenge is manifest in our trade deficits and silent factories and has been amply documented by the President's Commission on Industrial Competitiveness (1985) and the NAE Series on the Competitive Status of U.S. Industry (National Academy of Engineering, 1985a). Success in addressing this challenge will depend in large part on economic growth derived from engineering and scientific research and the application of the results of this research. Although the ability of U.S. industries to compete in world markets is significantly influenced by factors other than our engineering and science base, there is abundant evidence that technological leadership is essential to U.S. industrial competitiveness and productivity.

It is largely through engineering research and application that society reaps the benefits from investment in basic science. Engineering contributes to both a stronger research base and the skilled manpower that can translate research results into improved products, processes, and services. Preeminence in science alone does not guarantee technological advantage for the United States.

Federal support of U.S. engineering research and education during the past 40 years has been substantial and vital to their present vigorous state. Many federal departments and agencies support engineering activities, and few are without interest in the results of that support. The missions of some federal agencies are heavily technological, for example, the National Aeronautics and Space Administration, the Department of Defense, the National Institutes of Health, the Department of Agriculture, the Department of Energy, the Department of Transportation, and the Environmental Protection Agency. Federal laboratories and federally sponsored laboratories have developed a broad range of technological capabilities from inertial navigation to particle acceleration to pollution control. The system of research universities has become a national asset developed and supported largely by federal investment. Engineering education at the major research universities and, to a lesser extent, at smaller engineering colleges has been strengthened through a variety of federal mechanisms.

The United States clearly has fulfilled many of the policy objectives of the Bush report. We have produced a wealth of invention with consequent benefits to our economic growth, employment, and standard of living. But we need to ask ourselves in 1986 how federal policies for support of engineering research and education can provide a stronger framework for sustaining our technological future.

Engineering and science are a continuum. Knowledge about natural processes is derived from basic science and applied through engineering to meet the needs of society for products and processes. In turn, knowledge from engineering practice and the use of technology opens new possibilities for scientific theory and observation. Engineering and science advance in full partnership and share many requirements. Both engineering and scientific research demand a sound base in computation and mathematics. Both are enhanced by diversity in mechanisms for the conduct and support of research, and both benefit from consistent support for institutions involved in the exploration of new concepts and ideas. Both activities require modern and, in some cases, expensive facilities and instrumentation. In many key areas such as biotechnology, materials, and optoelectronics, combined efforts of engineers and scientists are required to advance the frontiers of knowledge and application.

Engineering and science share many needs and opportunities but also have significant differences. Training in engineering differs from that in science; whereas engineering places notably high values on undergraduate education and continuing education for life-long competence, scientific education centers on doctoral studies. The practice of the professions also varies, with science heavily concentrated in academia, and engineering diversified across industry, government, and academia. Most important, the objectives of engineering and science diverge in emphasis. Application is always a major goal of engineering.

The differences of degree and kind between the goals of engineering and scientific research call, in some instances, for different policies under which to support education and research in engineering and science. This report addresses some of those differences and suggests ways to strengthen federal policies that foster vital engineering research and education enterprises in the United States.

The Committee believes that the United States must be more aggressive in its support of engineering research and education and that the federal government can and must play a significant role in ensuring our technological future. It is time for national policy to emphasize the critical role of engineering—alongside scientific discovery—in building U.S. technological advantage.

ENGINEERING RESEARCH

Engineering research is a major factor affecting the status of engineering practice and technology. The present capability of our nation's engineering and technological enterprise is strongly dependent on effective federal and industrial support for engineering research. Engineering research is carried out in universities, federal laboratories, and industry, and federal support is channeled through the National Science Foundation (NSF) and a variety of mission agencies. Such diversity in funding mechanisms and research locations encourages diversity in research programs and fosters consideration of novel and unconventional ideas.

Federal support for engineering research can be made more effective in several ways. Particular attention should be given to the following: (1) balancing support for the spectrum of research opportunities, from large multidisciplinary engineering research centers to individual-investigator grants; (2) enhancing productive collaboration among university graduate students, faculty investigators, and engineers engaged in mission-oriented research and development; (3) improving federal institutional mechanisms for support of engineering research; and (4) early involvement of the research community in high-cost engineering projects.

In the discussion that follows, two themes stand out:

- It is essential to enhance communication across sectors among faculty members and students from universities and research engineers from industry and federal laboratories. Long-term, cooperative associations—both formal and informal—can improve the quality and ensure the relevance of engineering research.

- Stability of federal support is particularly important for engineering graduate study and for both disciplinary and cross-disciplinary engineering research. Because engineering research is commonly directed at defined problems and is appropriately responsive to short-term national and industrial needs, fluctuations in engineering research funding in particular fields are frequent and sometimes severe. Although these fluctuations may cause only a tolerable delay of expected research results, the damage to training and the flow of engineering talent can be serious.

Balancing Support for the Spectrum of Research Opportunities

The National Science Foundation supports basic research in universities principally through grants to individual investigators. Such grants are an essential funding instrument in engineering research, providing the system with fluidity and a rich diversity. These grants encourage individual initiative, allow a self-directed investigator to proceed rapidly down a chosen research path, and provide support for associated undergraduate and graduate students and postdoctoral fellows. A notable example is the National Science Foundation's Presidential Young Investigator (PYI) grant program, which provides support for promising young faculty members and promotes their collaborative interaction with industry. The Committee recognizes, however, that because PYI awards encourage the awardee to seek matching funds from industry, they may impose time-consuming fund-raising burdens that reduce the time that can be devoted to research and education.

Individual-investigator awards are particularly important sources of support for disciplinary research, although investigators may also pursue cross-disciplinary research. Adequate support for disciplinary engineering research will strengthen the disciplinary base and permit the engineering community to respond effectively to unanticipated short-term problems.

The Committee urges the National Science Foundation and other agencies to continue individual-investigator support for excellent young engineering faculty members through a variety of mechanisms. The Committee particularly recommends expansion of programs that give special support to young investigators, such as the NSF Presidential Young Investigator grant program. The PYI program also promotes cooperation between young faculty members and industry, and we urge the National Science Foundation to support programs that encourage similar cooperation for all faculty members.

The NSF has recently begun to fund more larger-scale, multidisciplinary research programs in engineering, including a total of 11 Engineering Research Centers (ERCs) established in 1985 and 1986. The NSF's purposes in supporting the Engineering Research Centers are to provide cross-disciplinary research opportunities for faculty and students, to promote cooperation between universities and industry, to enhance engineering education through involvement of undergraduate and graduate students, and to provide fundamental knowledge that will contribute to the solution of important national problems. These Centers make available to university researchers equipment and facilities essential for addressing multidisciplinary research opportunities and provide valuable opportunities for education near the cutting edge of practice.

The percentage of research funds allotted to larger group grants in the Engineering Directorate of the NSF has risen from essentially zero several years ago to approximately 9 percent in 1985 and could increase to 20 percent by 1990 if current trends continue. We agree with the view expressed by NSF Director Erich Bloch in support of cooperative, cross-disciplinary efforts:

> Within and outside the government, adversarial attitudes that block cooperation must be overcome—but without sacrificing our creative competitive drive or the distinctiveness of individual institutions. . . . This premise has prompted the National Science Foundation to devise programs that cross traditional institutional and disciplinary boundaries in such areas as biotechnology, materials science and systems engineering, and computational science and engineering. Arrangements bringing together a variety of actors are not new, although they used to be peripheral to the main research strategy. In the future, such strategies will become central (Bloch, 1986, p. 27).

The Committee endorses current and projected trends in National Science Foundation funding of multi-investigator and multidisciplinary engineering programs, such as the Engineering Research Centers. We also endorse the Department of Defense University Research Initiative.

However, multidisciplinary research centers located in universities and focused on industrial and national research problems have sometimes had difficulties in maintaining excellence and a sense of purpose. Sponsoring institutions should be encouraged to define criteria at an early stage for terminating or redirecting centers and center activities whose objectives have been changed or fulfilled. Sponsoring agencies should also be encouraged to identify research center topics that are broad enough to provide participants with the flexibility to pursue innovative research projects and to ensure that centers will have an effective lifetime of reasonable duration.

The NSF has adopted a farsighted procedure for review of the Engineering Research Centers to help make certain that ERCs achieve their objectives. Other federal agencies, such as the Department of Defense, have also begun to increase their funding and sponsorship of university-based engineering research centers. We recommend that these agencies also adopt review procedures that are appropriate to these new research centers.

Several key questions associated with multidisciplinary centers should be taken into account by program reviewers, sponsoring agencies, and host universities in their reviews of such centers. Are centers attracting outstanding faculty members? Are centers and participating faculty members retaining essential, close ties with relevant university departments? Are universities developing faculty evaluation procedures that appropriately value multidisciplinary center activities? Is participation in interdisciplinary research and multiauthor publications making it difficult for young faculty members to be promoted to tenured positions because such decisions are usually made in discipline-based departments?

The appropriate mix of engineering research funds—from single-investigator awards to cross-disciplinary, multi-investigator projects—will continue to be influenced by social need and technical opportunity, the demand for specialized facilities, and pressures from the engineering community. Properly handled, all types of research grants can effectively encourage individual initiative and provide excellent education for graduate students, and appropriate peer and institutional review can ensure that each award results in effective use of available research funds.

Improving Collaboration and Communication Between Universities and Mission Agencies

Engineering research sponsored by mission agencies and performed in federal laboratories is related to the solution of particular national problems and is commonly referred to as mission-oriented research. Much of the engineering research performed in federal laboratories is excellent, and we recommend two initiatives that may further enhance that quality.

First, we urge federal mission agencies to establish or increase their support for programs that encourage long-term collaboration and communication between university graduate students and faculties and engineers engaged in mission-oriented research. Mission-oriented research is conducted in a variety of settings—federal laboratories, industry, and universities—and we urge engineering faculty and student involvement in research activities in each of these settings. Such programs enhance the relevance of engineering education and university-based research and lead to recognition of other areas of research that are timely for investigation. They also help engineers involved in directed research programs identify university investigators engaged in research of intrinsic importance to the mission goal, thereby facilitating more rapid development of innovative technologies.

Second, we recommend that federal agencies be permitted to use procedures that will facilitate the conduct of mission-oriented engineering research in universities. Federal agencies often allocate research contracts by competitive bidding. Because competitive bidding on government contracts is not handled well by many universities, and because universities frequently choose not to become involved in classified research, there is a tendency for much mission-oriented research to be performed within an agency or in industry. The goal of this initiative is not to transfer research support from federal laboratories and industry to universities but to permit agencies in a timely and efficient fashion to fund research at universities whenever they are best qualified to carry it out.

Improving Institutional Mechanisms

Two questions stimulate consideration of the adequacy of current institutions for federal support of engineering research. Are there better means for funding agencies to identify research areas that are no longer productive and should not receive further support? Can we increase the probability that research leading to innovative technologies is appropriately funded?

Both questions must be approached cautiously. History gives examples of research disciplines that were considered by contemporary experts to be exhausted and were later revitalized by technological advances. Intellectual interest in engineering and scientific disciplines fluctuates, and support for those disciplines should naturally—perhaps slowly—evolve. Aside from national initiatives judged to be of strategic or economic importance, we urge that funding decisions continue to be strongly influenced by factors internal to the discipline or subject area and the rigorous filtering process that experts in the field can provide.

With regard to the second question, critics argue that merit is most difficult to identify in projects that are profoundly innovative and for which there are few knowledgeable experts or certain outcomes. Grants for basic engineering research are generally evaluated and awarded on the basis of rigorous peer review. But to maintain technological leadership, it is necessary not only to make incremental improvements in the current generation of technologies but to identify and assess new concepts and incipient technologies. *The Committee therefore urges federal agencies to consider their roles in enhancing support for innovative technologies.*

Specific cautions can be inferred, however, from the experience of the Department of Defense in funding research on innovative technologies through the Defense Advanced Research Projects Agency. For example, transferring the results of research to appropriate "customers"—mission-oriented services, agencies, or industry—is essential if the results are to do more than lie latent and unused. The subject of harnessing invention for the production of new and improved products and services should be considered further in any subsequent technology policy study by the Committee on Science and Technology of the House of Representatives.

We believe that the present federal organizational structure is capable of meeting the nation's needs in engineering research and education. Recent changes in the Engineering Directorate and the Organic Act of the National

Science Foundation demonstrate congressional and NSF recognition of the critical role of engineering research and education and the willingness of the Foundation to contribute even more to the nation's technological enterprise. We support the recommendations of an earlier NAE report (1985b) that encourages the NSF to achieve a more effective role in engineering and technology.

High-Cost Engineering Projects and Engineering Research

Large-scale, high-cost science and engineering initiatives serve a variety of important economic, social, engineering, and scientific ends. They may derive from market forces, from government initiatives, or from the scientific and engineering communities. Some of these projects include significant engineering research and development, and others do not. The projects also vary in the extent to which technologies of broad economic or social benefit can be spun off from the focused scientific or engineering objective. They can provide the impetus for technological breakthroughs, many of which may not be anticipated and some of which may be important to U.S. economic welfare and national security.

Well-managed large-scale projects can provide excellent engineering research opportunities if there is communication among the participants. Special care needs to be taken to ensure such communication when large-scale projects involve collaboration between academic and industry investigators. We wish to highlight our concerns about investment in, and conduct of, such projects.

Funds devoted to large-scale, high-cost scientific and engineering projects should not displace normal research funds. An agency's support for a large project should be augmented by support for research in fields that are opened by that project. Because large-scale projects are frequently of limited duration, stable support for engineering research at universities helps provide both the skilled manpower required to staff such projects and the research base to absorb displaced engineers when the project is complete.

Continued federal support for disciplinary and cross-disciplinary engineering research and development is essential to ensure a research base capable of supporting a variety of large-scale projects. Deficiencies in the research base can lead to serious difficulties in the conduct of large-scale projects.

We emphasize the importance of involving the engineering research community early in the consideration of large-scale, high-cost engineering projects. The National Research Council can provide a forum for discussion of engineering feasibility of many such efforts. Timely discussions can help

ensure that an adequate research base exists to support the development of a particular technological objective, facilitate critical analysis of the usefulness and economic feasibility of the project, and strengthen the contribution of the engineering research community from the initial stages of a project.

ENGINEERING EDUCATION

Effective education in engineering both follows from and proceeds in parallel with effective education in the basic sciences. The quality of engineering education is therefore linked to the quality of science education. However, excellence in science education does not by itself guarantee excellence in engineering education. Indeed, several of the most important determinants of quality in engineering education today are unrelated to science education.

In engineering, as in many other fields, the simultaneous pursuit of research and education has greater total effect than the sum of its individual effects. Research opportunities attract superior faculty members and students to a campus, and education will benefit. Similarly, research is made more effective by improvements in education. For example, the most immediate benefit to engineering research from effective engineering education in universities is through graduates who carry the knowledge newly acquired from their on-campus experiences to industry, to government, and to other universities.

The following six current issues are either unique or especially pertinent to engineering education: (1) shortages of faculty, (2) deterioration of facilities and instrumentation at universities and colleges, (3) the need for stability of federal support for engineering education and research, (4) the importance of life-long education for engineers, (5) the inadequacy of preengineering and engineering course material and programs to serve precollege and undergraduate students, and (6) the need to increase the relevance of engineering education to the nation's industrial competitiveness. Each of these issues represents opportunities for action by the federal government to strengthen engineering education and thereby increase the technological competence of the nation's engineering work force.

Shortages of Faculty in Engineering Schools

The National Research Council Committee on the Education and Utilization of the Engineer described the current shortage of engineering faculty as the most pressing problem in engineering education. Out of a total U.S. engineering faculty of approximately 18,000, estimates of the shortage range from 1,567 (the number of unfilled positions reported in a 1983 survey of engineering deans) to 6,700 (the number necessary to reestablish the 1967–1969 and 1975–1976 student/faculty ratios) (National Research Council, 1985). A recent survey of engineering colleges revealed that 8.5 percent of budgeted faculty positions were unfilled in the fall of 1983 (American Society for Engineering Education, 1984), a value significantly greater than the estimated typical 3 or 4 percent (National Research Council, 1985). Faculty shortages vary widely across engineering disciplines, and are most acute in fields such as electrical engineering and computer science.

One important reason for the shortage of engineering faculty is economic: for particular engineering disciplines, average academic salaries are significantly below those offered by industry. As the report by the Committee on the Education and Utilization of the Engineer concluded:

> The salaries of full professors are well below those of their counterparts in industry. Moreover, the key salary problem is with junior faculty—assistant and associate professors beyond the entry level—and this is of course what discourages many young Ph.D.s from considering teaching as a career (National Research Council, 1985, p. 56).

In addition, many bachelor's and master's degree engineering graduates are not inclined to continue graduate studies that may lead only to marginal gains in compensation. A recent survey revealed that the median salary for engineers 10 years after receiving their bachelor's degrees was $38,100 for those with master's degrees, and only $3,300 more—or $41,400—for those with Ph.D. degrees (Babco, 1985). It is estimated that a Ph.D. engineer does not surpass the total accumulated earnings of a B.S. engineer until about 21 years after each has received the B.S. degree (National Research Council, 1985).

A further disincentive to academic careers is that research equipment and facilities in engineering colleges are generally poorer than those available in industry. Engineering research projects that require the supporting infrastructure available in leading industrial laboratories often cannot be carried out effectively in universities.

The lack of sufficient faculty is an important factor currently limiting attempts to increase the quality, scope, and number of engineering programs. The continuing need to replace retiring faculty members will exacerbate this problem. Faculty shortages also are made more severe by the increasing percentage of graduating Ph.D. engineers who are foreign nationals. Foreign nationals currently make up between 40 percent (National Research Council,

1985) and 50 percent (Bloch, 1986) of Ph.D. engineering graduates. However, the problem is not that foreign Ph.D. students are displacing U.S. students in universities. Instead, it is that the percentage of qualified U.S. engineering students who elect to pursue the Ph.D. degree is declining. The projected supply of 4,000 Ph.D. engineering graduates per year will be inadequate to meet the nation's needs, particularly the needs of academia and government in a competitive employment market (National Research Council, 1985; National Academy of Engineering, 1985b). Programs that encourage mid-career and retired engineering professionals with practical, nonacademic work experience to teach part-time in colleges and universities could help meet some of the demand for engineering faculty.

Although an increase in academic salaries may be justified to attract qualified Ph.D.'s to universities and to encourage excellent bachelor's and master's degree candidates to pursue Ph.D. degrees, the incentive to pursue a career in teaching and basic research has never been, and should not be, only economic. The opportunity to define and carry out engineering research without the tight organizational controls characteristic of industry will remain critical to the choice of an academic career. This opportunity is strongly dependent on federal support of university-based research. The federal government can enhance the quality of engineering education by strongly supporting university-based engineering research.

Deterioration of Engineering College Facilities and Instrumentation

Obsolescence of laboratory equipment is a serious problem in undergraduate and graduate educational institutions in general (Office of Science and Technology Policy, 1986). This was identified as a particular problem for engineering schools in the 1985 National Research Council report *Engineering Education and Practice in the United States* and again in a 1985 NAE report (National Academy of Engineering, 1985b). Although the average useful life span of laboratory equipment is currently about 10 years, the average age of laboratory equipment in engineering schools nationwide is 20 to 30 years (National Society of Professional Engineers, 1982). Governmental and industrial support programs in this area have been so sporadic that a serious mismatch exists between the need for equipment and the level of available support (National Research Council, 1985).

The federal government can enhance engineering education and research by increasing support for instructional and research facilities and equipment at engineering colleges and universities. New directions taken by the federal government in support of engineering research, such as the Engineering Research Centers program at the NSF, will help address this problem. *In* *addition, the Committee urges federal agencies to expand programs that provide equipment—both software and hardware—to universities in support of engineering projects to help alleviate the problem of equipment obsolescence.* ARPANET, the university-government telecommunications network that interconnects computers across the nation, is an example of such a software program.

A related problem is the deterioration of engineering school facilities. The federal government has not provided facilities support in recent years, and we urge a change in this practice. *We encourage the National Science Foundation and appropriate federal agencies to support innovative programs of government-industry-university financing, including matching grants and broader cost-allowability for alternative financing methods that address both equipment obsolescence and facilities deterioration in engineering colleges and universities (National Research Council, 1985).*

The Need for Stability of Federal Support for Engineering Education and Research

Engineering enrollment is sensitive to fluctuations in the market demand for engineers. These fluctuations emphasize the capability of the engineering work force to adapt to changing national needs and maintain a reasonably close balance between supply and demand for engineering graduates. The engineering work force has demonstrated resiliency when new technologies are introduced (the substitution of transistors for vacuum tubes in the 1950s), when cross-disciplinary movement is required (the start of the manned space program in the late 1950s), and during periods of national need (the energy crisis of the mid-1970s). Periodic imbalances in supply and demand for engineers in industry may present temporary problems to particular industries but appear to be recurrent and are usually self-correcting in the long run.

The Committee concludes that fluctuations in demand for the engineering work force do not require federal attention but recognizes that rapid shifts in enrollment in engineering disciplines may significantly strain the educational system. The National Research Council Committee on the Education and Utilization of the Engineer explained the problem as follows:

> The perception of shortages and surpluses of engineers in certain fields (and the accompanying sense of excitement or disdain among students) has a dramatic impact on patterns of demand for particular courses of engineering study. Enrollments in electronic and computer engineering, for example, are saturated at most schools. The fact that the student response is usually out of proportion to the actual stimulus, combined with the fact that the response lags the stimulus by as much as four years, has the effect of wasting educational resources and engineering talent. Institutions cannot adapt to external conditions as rapidly

as they develop; thus institutional stresses of this sort appear to have become a permanent feature of the contemporary educational environment (National Research Council, 1985, p. 67).

As important as the question of quantity is the question of quality. The White House Science Council Panel on the Health of U.S. Universities and Colleges recently issued a report recommending that a substantial program of merit-based, portable scholarships be established by the federal government at the undergraduate level and that multiyear merit-based graduate fellowships be established in engineering, science, and mathematics (Office of Science and Technology Policy, 1986). *We concur with these recommendations and suggest that multiyear support for meritorious engineering graduate students by the National Science Foundation and appropriate federal agencies—with stipends substantial enough to attract the top U.S. students—may encourage more U.S. students to pursue Ph.D. degrees.*

Federal support for meritorious undergraduate and graduate students and for research should be determined largely by factors internal to a particular engineering discipline and subject to appropriate peer review. However, this Committee believes that strains on engineering schools from recurrent fluctuations in market demand for engineers can be ameliorated through greater stability of financial support for undergraduate and graduate students and for university-based engineering research. Such stability will permit more efficient use of both financial and human engineering resources. *The Committee encourages federal agencies to promote continuity in funding engineering education and research. We endorse, for example, the recent proposal by the White House Science Council Panel on the Health of U.S. Universities and Colleges that federal funding agencies extend average research grant durations to three—and preferably five—years (Office of Science and Technology Policy, 1986).*

Among the highly desirable means to enhance the flow of talent are programs that encourage women and minorities to become engineers. Currently, only 5.7 percent of engineers are women and 4.6 percent are minorities (National Research Council, 1985). These groups represent an appreciably smaller fraction of the engineering work force than they do of the science and professional work forces. Efforts that were begun in the early 1970s to increase participation of women and minorities in engineering have been somewhat successful. The proportion of engineering undergraduate students who are women has risen from 1 percent in 1970 to 15 percent today. These efforts should be continued and strengthened.

The Importance of Life-Long Education for Engineering

Despite the rapid expansion of scientific and engineering knowledge that characterizes the current era, the average duration of an engineer's formal study has not increased significantly in the last 30 years. In the past decade, however, chief executive officers, practicing engineers, and universities have placed increasing emphasis on continuing education. The National Research Council Committee on the Education and Utilization of the Engineer summarized the need for continuing education as follows:

> The underlying reasons for this growing emphasis on continuing education and professional development include the rapidity of technological change in every field of engineering, the introduction of computers (with their widespread impact on every discipline), the increasingly interdisciplinary nature of engineering work, and increased world competition in engineering requiring greater engineering performance. None of these underlying causes will disappear in the future. If our goal as a nation is to maintain a strong engineering work force, continuing education will have to play a vital role (National Research Council, 1985, p. 71).

Effective continuing education throughout a career in engineering can encourage the professional flexibility that will enable engineers to anticipate changing demand and avoid technological obsolescence. In addition, continuing education programs enable engineers to remain productive throughout their careers.

The lack of company reimbursement and release time can be a strong disincentive for pursuing continuing education (National Research Council, 1985). *The Committee urges the federal government to support the development of a system for life-long engineering education by providing incentives for companies, universities, and individuals to invest in such programs.*

The Place of Engineering in Precollege and Undergraduate Education

The effectiveness of graduate engineering education depends on the adequacy of both precollege and undergraduate preparation. Early exposure to mathematics and the sciences is an important factor in students' decisions to pursue, and their ability to complete, undergraduate engineering degrees (National Research Council, 1985). Although secondary school curricula contain basic science courses (such as chemistry and physics) and some technical courses (such as drafting and computer programming), the majority of secondary schools make little or no effort to expose students to contemporary engineering problems. High school students can take courses in the biological sciences and the earth sciences, but similar courses for the technological sciences are unavailable. Many secondary school students thereby miss an opportunity to prepare for a college program in engineering.

Secondary schools are likely to remain limited in their ability to provide students with relevant engineering experience because they lack skilled instructors and appropriate equipment, facilities, and course materials. It would be valuable for secondary schools to participate in cooperative programs with local colleges, federal laboratories, and industries whereby promising students could be involved in engineering projects during the summer and school year. *The Committee recommends that the Department of Education and the National Science Foundation help to develop such programs.* The technological literacy derived from such programs is important not only for the engineering work force, but for our population as a whole.

Relevance of Engineering Education to the Nation's Industrial Competitiveness

We have emphasized the need to increase the number of Ph.D. graduates in engineering and to attract those graduates to academic careers. We also recognize that an important distinction between graduate science and engineering education is the demand for professionals holding master's degrees. The master's degree offers practicing engineers a level of specialization and career versatility that has become increasingly attractive in light of the multidisciplinary and complex nature of engineering practice today. In some areas of chemical and civil engineering, aeronautics and astronautics, and in most fields of electronics and computer engineering, the M.S. degree has become the standard level of academic preparation for those engaged in design work (National Research Council, 1985). A terminal master's degree in the basic sciences is usually of significantly less employment value than a master's degree in engineering. *There is a need to recognize the value placed on the master's degree in engineering by industry, and we urge that ways to increase the availability and quality of engineering master's degree programs be developed.*

The Committee believes that the present level of production of Ph.D.'s in engineering is inadequate to meet future industrial, academic, and governmental needs. A high priority must be set on providing essential support to graduate engineering students pursuing the Ph.D. degree.

Industry employs more than 70 percent of those engineers with a Ph.D. degree, perhaps recognizing the particular advantages of advanced training in highly specialized areas of technology. Salary surveys indicate, however, that companies commonly do not place significant commercial value on the three years a student spends in a university pursuing that degree. Several factors contribute to this situation. For example, engineers with master's degrees are usually more willing than Ph.D.'s to participate in directed research and development projects that are common in industry.

Many industries do not understand how academic research training beyond the master's degree provides the engineer with a commensurate increase in knowledge relevant to industrial needs. To respond to this situation, and because of the pressure of foreign competition in engineering-intensive industries, the federal government has recently begun to encourage closer interaction between industry and universities (National Research Council, 1985). Examples are the National Science Foundation's support for on-campus Engineering Research Centers, the Department of Defense's University Research Initiative, and the administration's support of closer collaboration between federal research laboratories and their university and industry counterparts. We encourage these initiatives.

In addition, individual students and faculty members should be encouraged to establish lasting ties with peers in industry and mission agencies. Federal mission agencies should be encouraged to increase funding for projects initiated by engineers in federal laboratories or in industry and involving collaboration with university investigators.

The Committee recognizes that institutional impediments to such interaction may exist: industrial support of university research has sometimes been sporadic and unstable, industrial activities are often highly specialized and may not contribute to the university's pursuit of generalizable knowledge, and young faculty members seeking tenure may be particularly constrained in developing cooperative research programs that do not follow traditional, disciplinary models. Nevertheless, the Committee believes that such programs can do much to ensure that engineering education produces graduates capable of transferring innovative technologies from university research laboratories to industrial practice and national service. Educational and research programs of the universities will also be strengthened by such programs. Finally, we emphasize that federal programs to encourage interdisciplinary and multidisciplinary research need to be matched by flexibility and innovation on the part of educational institutions to fit such programs into the total institutional environment.

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