New Directions for Engineering in the National Science Foundation: A Report to the National Science Foundation from the National Academy of Engineering (1985)

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New Directions for Engineering in the National Science Foundation

A REPORT TO THE NATIONAL SCIENCE FOUNDATION FROM THE NATIONAL ACADEMY OF ENGINEERING

Prepared by
National Academy of Engineering.
Committee to Evaluate the Programs
of the National Science Foundation
Directorate for Engineering

National Academy of Engineering
Washington, D.C. 1985

The National Academy of Engineering is a private organization 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. This collaboration is implemented through the National Research Council. The National Academy of Engineering recognizes distinguished engineers, sponsors engineering programs aimed at meeting national needs, and encourages education and research.

This report has been reviewed by members of the National Academy of Engineering other than the authors. 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.

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Office of the President

April 18, 1985

Dr. Nam Suh
Director, Engineering Directorate
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

Dear Dr. Suh:

The National Academy of Engineering is pleased to submit the report New Directions for Engineering in the National Science Foundation. The report responds to your request to review the plans of the Engineering Directorate of the National Science Foundation and the recently adopted engineering program structure. You also requested the Academy's views on appropriate funding levels.

The Academy has addressed these questions through a committee of members of the NAE, chaired by Dr. Peter Likins, President of Lehigh University. The Academy found the task both challenging and difficult. We are convinced that the long-term national well-being is directly dependent upon a healthy and vigorous engineering research and education undertaking. The U.S. can preserve and advance its competitive edge only through an education and research system in both universities and industry dedicated to the development of outstanding talent that can operate at the cutting edge of scientific and engineering knowledge, and produce the innovative technological advances on which economic growth depends.

Our assessment is that the directions now being taken by the National Science Foundation, implied by the new program structure of the Engineering Directorate, are a healthy response to both opportunities and problems enunciated above. While endorsing the new shape of engineering at the NSF, we urge that the new directions implied by the restructuring of the programs of the Engineering Directorate not result in the lessening of the support for the basic engineering disciplines on which all interdisciplinary engineering depends. The funding made available to the Engineering Directorate must sustain these dual needs.

The most difficult question faced by the committee related to the level of funding that would be required for the Engineering Directorate to build an engineering program commensurate with the NSF's responsibilities in assuring the health of the national engineering research and education enterprise. The committee, recognizing the large responsibilities and programs of other federal agencies, as well as the difficult budgetary conditions that face the nation, has sought therefore to assess minimum needs. Larger appropriations could be beneficially used. We have sought to buttress our analysis by clear statements of assumptions that underpin the estimates.

Under the assumptions made by the committee, its assessment is that the budget of the Engineering Directorate should increase to a level around $400 million by FY 90--5 years hence. We believe that at this level of funding for the Engineering Directorate, the NSF can address many of the major opportunities for strengthening engineering research and education in this nation which are reasonably its responsibility.

The total engineering effort of the NSF also involves programs which are funded and managed outside of the Engineering Directorate. The committee addressed some of these programs and associated needs--for example, graduate fellowships, instructional equipment, and midcareer fellowship opportunities, as well as facility deficiencies. Only funding for the graduate fellowships has been addressed in this report. The NSF needs to examine the programmatic and funding needs of these other engineering activities as well.

The question of the NSF role in undergraduate engineering is one that merits further exploration. While the committee emphasized training and research related to graduate education, it also points out the importance of undergraduate education for the practice of engineering. The Engineering Research Centers are a positive step in improving the full spectrum of engineering education in U.S. universities, and we must continue to think of imaginative approaches to improving our engineering colleges, as well as graduate schools.

Finally, let me also bring to your attention the high priority that the committee gives to computer and information technology. This is an area where the NSF has taken major steps to strengthen its program. However, it is an activity that in the opinion of the committee has such a pervasive effect on engineering and scientific work that a review of the total scope of NSF's computer and information programs to consider their further strengthening and overall coordination may be desirable.

It is my hope that this report will be useful to the National Science Foundation, to the federal government, and to the community which looks to the NSF for its support. The NAE has valued this opportunity to serve the NSF.

Sincerely,

Robert M. White
President

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PREFACE

This report is a response by the National Academy of Engineering (NAE) to a request from the National Science Foundation (NSF) under the cooperative agreement of NSF in the field of engineering and technology with NAE and the National Academy of Sciences. More specifically, NSF sought assistance in reviewing and analyzing the current and planned programs within its Directorate for Engineering. In particular, the NSF assistant director for engineering asked NAE to form a committee to provide advice on future challenges and national needs, opportunities for the various fields of engineering, strengths and weaknesses of NSF engineering programs, new NSF initiatives relating to critical and emerging technologies, and long-term resource requirements.

The work of the committee was undertaken in a context shaped by two major studies already in progress under the sponsorship of the National Research Council:

1. The Engineering Research Board (ERB) and its seven panels have begun a comprehensive study of engineering research in the United States. This study, which covers research supported by both government and industry and conducted in academia, industry, and government, is evaluating research in bioengineering; transportation; manufacturing; energy, resources, and environment; materials; information, computation, communication, and control; and construction and structural design. The reports of the ERB should be of special value in identifying emerging research challenges.

2. The Committee on Education and Utilization of the Engineer and its nine panels are engaged in a comprehensive study of the entire engineering community in America, with emphasis on education, training, and employment. The reports of the committee will contain numerous suggestions for increasing and maintaining the lifelong productivity of engineers. It is likely that several proposed initiatives will be directed to the NSF Directorate for Engineering.

Some general views on the subject of strengthening engineering in the National Science Foundation were expressed by the NAE president in a 1983 report,[1] and specific guidelines for the implementation of recommendations on cross-disciplinary research followed in a report entitled Guidelines for Engineering Research Centers.[2] The Foundation successfully secured $10 million in new funds to begin to implement these recommendations, and the establishment of an initial set of NSF Engineering Research Centers is under way.

In the fall of 1984 the Academy was requested by the new leadership of the Foundation and its Directorate for Engineering to organize consultations required for prompt review of NSF plans in the formulation stage. That request gave birth to the NAE Committee to Evaluate the Programs of the NSF Directorate for Engineering, which submits this report on the basis of its meetings in December 1984 and January 1985.

Readers will note that a large proportion of the report is devoted to the question of resource needs. While the committee attaches great importance to each of the areas about which NSF sought guidance, we believe that the issue of resource requirements needs the most detailed analysis. Our discussion of resource requirements, however, does not entirely answer questions of priorities among areas that might receive added resources. We have focused on the broad scope and character of the NSF Directorate for Engineering. Subsequent efforts, both within and outside NSF, must tackle the issue of priority at more specific levels.

While the committee devoted considerable discussion to the recent restructuring of the Directorate for Engineering, these discussions are not reflected in detail in this report. There are numerous advantages and disadvantages to any reorganization, and we concluded that extensive presentation of the issues would be less valuable than emphasis on defining what we believe the directorate should achieve and what resources it would take to do so. Undoubtedly, new issues will arise with regard to structure, and we expect NSF to be flexible if the issues prove to be serious.

Let me express my thanks to the committee members, who worked with diligence and readiness most gratifying to a chairman; to Nam Suh, William Butcher, and Paul Herer of the NSF Directorate for Engineering, who were most responsive and candid with regard to a range of queries and requests; and to Jesse Ausubel and Susan Skomal, who coordinated the project for the NAE.

Peter W. Likins
Committee Chairman

COMMITTEE MEMBERSHIP

National Academy of Engineering Committee to Evaluate the Programs of the National Science Foundation Directorate for Engineering

Peter W. Likins (Chairman), President, Lehigh University
William G. Agnew, Technical Director, General Motors Research Laboratories
Arthur G. Anderson, Retired Vice President, IBM Corporation
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Morris A. Steinberg, Vice President, Science, Lockheed Corporation
H. Guyford Stever, President, Universities Research Association; Foreign Secretary, National Academy of Engineering

EXECUTIVE SUMMARY

The recent evolution of engineering programs in the National Science Foundation (NSF) provides evidence that the Foundation is responding to important national and intellectual challenges with increasing vigor. The committee is impressed with the seriousness with which the NSF Directorate for Engineering is reexamining itself and with the boldness of its plans for improvement. We believe that the new directions proposed for NSF's Directorate for Engineering and the plans for implementation form the basis of an intellectually and fiscally sound program that will strengthen the national research base essential to our country's future prosperity.

Many have debated the nature of the relationship between engineering research in universities and the technological competitiveness of industry. We are convinced that, over the longer term, the knowledge base resulting from a strong and well-oriented university engineering effort undergirds the productivity and competitiveness of U.S. industry. Perhaps even more importantly, research provides the environment within universities that anchors quality engineering education, for it enables engineering faculty and advanced students to deepen and broaden their knowledge and to develop their capacity for creative work. These are underlying premises of the programs of NSF's Directorate for Engineering, and we endorse them unanimously.

At the same time, we recognize that it is equally important to maintain the traditional academic motivation: the search for knowledge driven purely by the creativity and imagination of the investigator. In its engineering programs NSF must seek with special sensitivity to achieve a good balance between the twin motivations of potential utility and intellectual endeavor. Success in this regard will require a combination of well-articulated policy and many informed decisions by researchers, proposal reviewers, and staff.

We note also the need to balance another set of efforts: those seeking to break new ground and those directed toward systematic deepening and strengthening of the bases of established disciplines. Progress in all fields of knowledge results from combining moments of extraordinary progress with enduring periods of diligence in gathering information and consolidating the knowledge base. It would be unwise for NSF to confine its attention to new initiatives billed as "breakthrough research."

If the NSF Directorate for Engineering is to achieve its potential for contributing to the advancement of national priorities, it must receive a clear charge and the resources to realize its objectives. In the past, NSF's role in engineering has been principally to fill in the gaps in fundamental knowledge left unexamined by others; its response has been largely reactive. NSF should continue to avoid undesirable duplication of effort, but in the current picture the gaps have widened so greatly that large opportunities exist for focused fundamental engineering research in emerging areas of technology.

Viewed against the background of the increasingly crucial role played by computers in engineering, the committee notes that it is particularly evident that NSF engineering commitments for computer and information engineering still fall short of needs. The committee recommends that the NSF director evaluate the adequacy of current NSF resources and structure for dealing with the magnitude and complexity of the computer issue.

In our opinion, much more basic work must be done in the future to prepare this nation to meet the technological challenges that lie ahead, and the NSF Directorate for Engineering should assume a greater share of this responsibility. In the course of the next five years the work of the Directorate for Engineering should increase substantially. In the judgment of the committee, expanded NSF programs in engineering research and education should have great leverage in strengthening the nation over the long run.

We propose the development of separate, coordinated plans for addressing operating and capital needs. A real growth in the operating budget from $142 million in FY 85 to between approximately $350 million and $410 million per year over five years is estimated as necessary. At the same time, NSF should take a leading role in meeting what we assess as a billion-dollar national problem of capital needs for academic engineering research equipment and instrumentation. We believe that other federal agencies should also move forward vigorously to meet the needs in the area of research equipment. If NSF were to continue to assume its current, one-sixth share of the federal responsibility in the engineering research equipment area, then over a five-year period a commitment of some $160 million would be required, and the combined operating and capital budgets for the NSF engineering directorate five years hence would likely be approximately $380 million to $440 million. These estimates establish a lower bound for the Directorate for Engineering, as the committee believes that NSF should assume more than its current, one-sixth share of the capital investment responsibility in academic engineering. Moreover, the range does not include important NSF responsibilities in engineering that are addressed largely outside the engineering directorate, for example, graduate fellowships, midcareer fellowships, instructional equipment, and facilities.

NATIONAL TECHNOLOGICAL CHALLENGES OF THE 1980s

Major national challenges of this decade include the need to increase the economic well-being and security of our country in the face of increasing international competitiveness and the need to improve the quality of life. These challenges can be met only if we can achieve the goals of lower cost, higher quality, and improved performance in our goods and services and acquire new knowledge to cope with problems as they arise in the pursuit of these objectives. Technological advances and strengthened engineering practice are primary means to these ends. To meet the challenges successfully will require a long-term national investment by both government and industry in our national technological base.

Five important ways that NSF programs can improve our technological base are as follows:

1. Strengthen research programs in basic engineering disciplines.
2. Develop strong interdisciplinary and systems engineering research activities and curricula at colleges and universities.
3. Strengthen relations between industry and universities, particularly in design, processing, and manufacturing engineering, and develop the science base in these fields.
4. Improve the attractiveness of faculty and graduate engineering opportunities to the best minds in America.
5. Improve the physical facilities and equipment for engineering research and instruction in our universities and colleges.

Increasingly, U.S. universities and colleges have been unable to afford the equipment required to provide hands-on experience to engineering students. Thus, engineering education has provided inadequate exposure to the instruments, systems, and processes of modern technology, and there has been a lack of practical experience among graduates. Needs for engineering equipment and instrumentation for training have been identified repeatedly as critical for the future health of our industrial enterprise.[3]

Closely related to the problems of inadequate equipment and instrumentation are the deficiencies of space and modern facilities for engineering research and instruction. Needs for renovation of facilities and for construction of new facilities have been assessed by the White House Science Council Panel on the Health of the Universities and Colleges as a $7-billion to $20-billion problem,[4] and a significant share of this total must be assigned to engineering. Whereas engineering schools have turned to industry with some success for help in meeting equipment needs, there seems to be no proper place for many schools to turn for needed construction and renovation of facilities. State governments play a major role in the facilities area, but the problem extends well beyond their resources and responsibilities.

In recent years both industry and universities have become aware of the benefits of closer ties; this trend must be encouraged. Closer relationships--whether they involve cooperative research programs, research contracts, grants for selected programs and equipment, continuing education, shared facilities, or faculty consulting--provide faculty insight into industrial problems while providing industry access to academic research capabilities and students.

A major difference between traditional academic research projects and industrial programs is the inherently interdisciplinary nature of the latter. Students and faculty would develop a much clearer understanding of industrial problems if they could structure research projects that span traditional disciplines and require integration of several elements into a coherent system.

According to the National Research Council's (NRC's) Committee on Education and Utilization of the Engineer,[3] awards of bachelor's degrees in engineering by U.S. academic institutions increased from approximately 43,000 in 1973 to approximately 72,000 in 1983. Moreover, subjective experience suggests that engineering disciplines are attracting a growing share of the top-quality echelon of the student population. In the same 10-year period, however, as indicated in Figure 1, there was a decline in the number of engineering doctorates awarded in this country, from approximately 3,600 to approximately 3,000. Moreover, as shown in Figure 2, the percentages of these degrees awarded to foreign nationals increased from approximately 30 percent to approximately 50 percent in the same decade.

It is of paramount importance that an appropriate percentage of engineering students go on to complete graduate school, in order to replenish an already depleted university and college faculty population, to anticipate the retirement wave in the

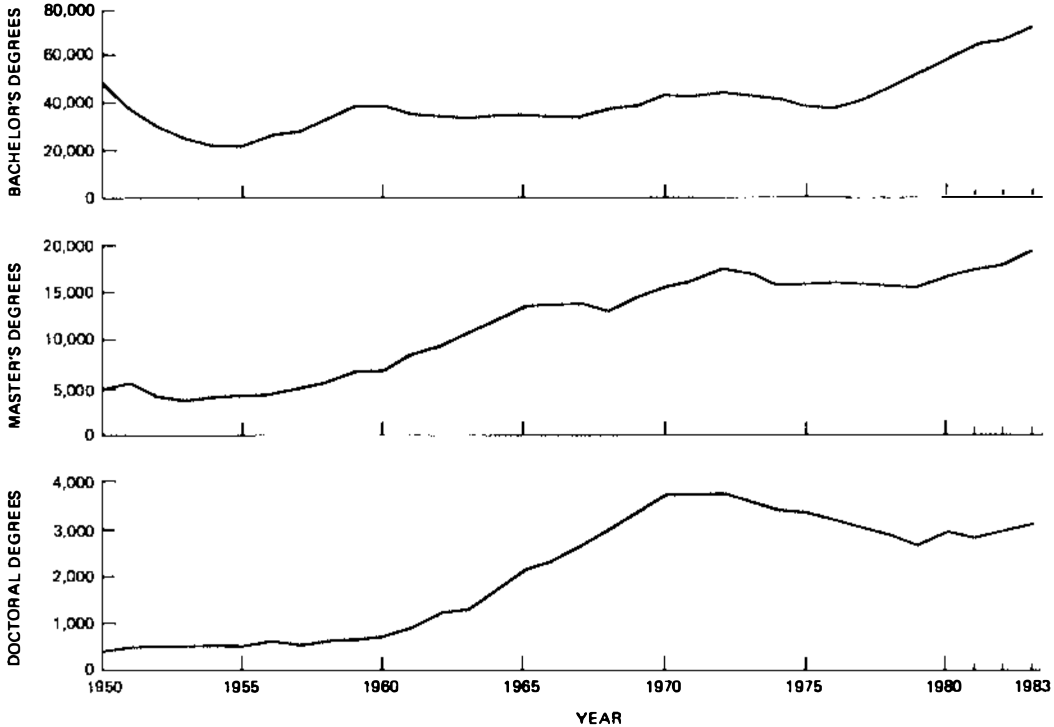

FIGURE 1 U.S. engineering degrees, 1950-1983.

SOURCE: Based on Reference 3.

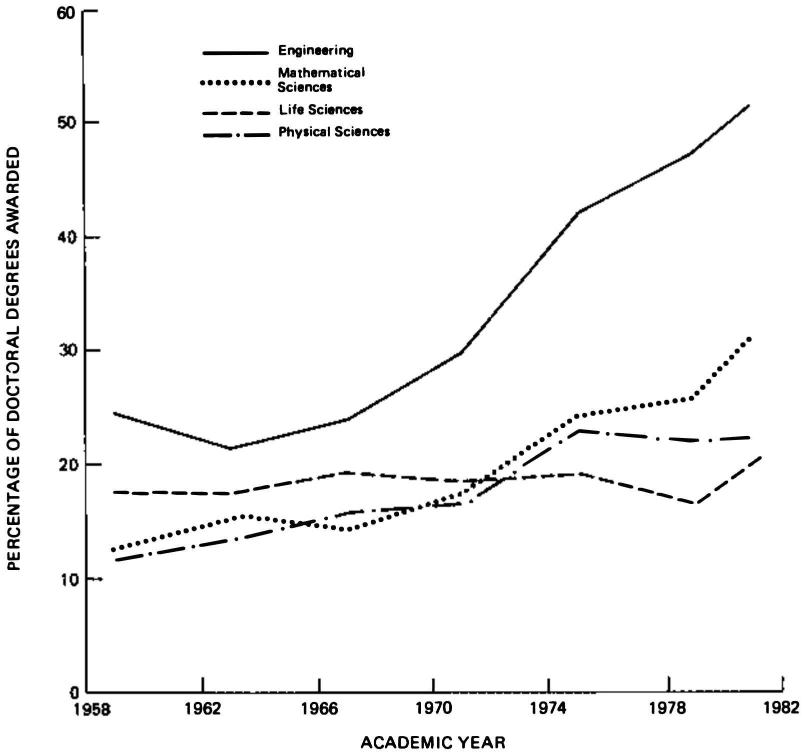

FIGURE 2 Foreign students receiving doctorates in American universities as fractions of the total number awarded.

SOURCE: Data from National Science Foundation.

professoriate, and to provide the highly trained people required by government and industry.[3,5] Yet, for a variety of reasons including the difficulty of finding support for graduate programs, coupled with attractive industrial offers for employment, the ratio of Ph.D. degrees to B.S. degrees awarded decreased from about 0.08 in 1973 to about 0.04 in 1983. There are now signs of a reversal in this trend. The increased support to graduate schools of engineering discussed in this report would be a powerful means to sustain these encouraging developments.

The strengthening of our engineering educational system would be reflected in the quality of our engineering work force, which in turn would improve the quality, cost, safety, and utility to the consumer of our goods and services; these improvements would then improve the international competitiveness of American business and positively affect our quality of life. The next question, of course, is the implication of these observations for NSF's Directorate for Engineering.

NSF ENGINEERING: PAST PATTERNS

One cannot properly assess the future role of the National Science Foundation in engineering without first pausing to assess its history. Accordingly, the committee gave careful attention to the evolution of engineering in the Foundation, noting its growth from a subsidiary program to a section, then to a division, and finally to one of the five research directorates. Even with this growth, however, the engineering directorate's budget remains at about 10 percent of the total NSF budget (10.6 percent in the proposed FY 86 budget).

A relatively small government agency, NSF provides about 15 percent of the federal research and development (R&D) obligations to colleges and universities ($759 million out of $5,021 million in FY 83).[6] When considered in the context of federal R&D funding for all of academic engineering, the role of the NSF has also been correspondingly modest (about $100 million out of $913 million--11 percent in FY 83), and in some fields (such as computer engineering) the support of the NSF has been a tiny fraction of the national academic research total. To establish the modest scale of operations of the NSF Directorate for Engineering in broader terms, note that its FY 85 budget at about $142 million[7] is approximately one-quarter of 1 percent of the total federal R&D obligation (about $53 billion) for FY 85 and about 3 percent of the total federal commitment to university research for FY 85, again assuming an overall budget of about $5 billion.

Nonetheless, NSF has served well in certain important fields of engineering research, providing continuing support in basic disciplines not readily sustained by the better-funded but often highly applied, mission-oriented agencies. Whereas in certain areas of science (such as ground-based astronomy) NSF has been the central research-funding agency, in engineering its role often has been viewed as focusing on any areas not adequately covered by mission-oriented agencies. Often that role has produced NSF support for research at the interface between science and engineering.

Over the years, the NSF Directorate for Engineering seems to have responded to the pressures of small budgets and large responsibilities by growing cautious, and even conservative, in its commitments. Individual allocations for facilities and major equipment (exceeding $100,000) have been very few, with only about $2 million for these purposes proposed for FY 86, an increase over budgets of less than $1 million in FY 84 and FY 85.[8] The central business of the directorate has been to dispense relatively small grants (typically $60,000 to $70,000 per year currently) to individual principal investigators submitting for peer review sound, relatively low-risk proposals directed toward research in the core disciplines of engineering science. Prior to the reorganization of the directorate (see section below on "Goals and Objectives"), its divisions matched the traditional or "founder" departments of engineering schools (mechanical, civil, chemical, and electrical engineering). It seemed even more difficult to obtain funding for research in nontraditional fields, often interdisciplinary, from NSF than from other government agencies. The resulting pattern of support has sustained research of consistently high quality in the traditional engineering disciplines in response to very rigorous disciplinary competition. This support has been very modestly and selectively supplemented by funding interdisciplinary projects or research on emerging needs, such as robotics and production technology, and on national needs, such as earthquake engineering studies.

NSF ENGINEERING IN TRANSITION

The job of providing the fundamental technical basis for continuing world leadership in industry is formidable. It must involve sustained commitment to engineering education, research, and practice by industry, academia, and several levels of government. With its prestige and visibility, NSF can play a key role, but our expectations for the country cannot be built on the efforts of one federal agency. NSF's efforts must be matched and amplified by the efforts of industry and many others if this country is to meet its goals.

At the same time, it would be a serious mistake to dismiss NSF's potential contribution in shaping the national response to the challenges of these times. NSF has earned the respect of the academic community for the quality of its people and the integrity of its procedures. And it is an agency in transition, with highly qualified new leadership ready to take on new challenges in engineering in its quest for a broader national mission.

The National Science Foundation is now positioned to become truly a national foundation for science and engineering, by whatever name.

GOALS AND OBJECTIVES OF THE NSF DIRECTORATE FOR ENGINEERING

In its FY 85 "Guide to Programs," NSF states four objectives to describe its activities:

1. Advance fundamental knowledge of engineering principles that will be applied to the analysis and design of a large variety of man-made devices, systems, and processes.
2. Strengthen the academic engineering research base and address the need for more basic research to underlie industrial technology innovations.
3. Create an improved research environment that will encourage larger numbers of engineers to seek graduate education and academic careers, as well as pursue research.
4. Stimulate the application of engineering knowledge to the solution of significant problems of national interest.

Providing more detail to these broad policy statements, the Directorate for Engineering[9] has identified the following specific goals:

- Strengthen support for basic research in engineering disciplines that have established science bases.
- Support research to establish science bases in engineering fields that do not yet have adequate foundations (e.g., design, manufacturing engineering, computer engineering).
- Foster the development of engineering research bases for potentially important emerging industrial fields (e.g., biotechnology).
- Support fundamental research to advance technological solutions for critical national problems (e.g., hazardous waste disposal).
- Support efforts to achieve major breakthroughs that radically improve international competitiveness of U.S. industries and the capabilities of essential industries (e.g., steel).

- Administer the Engineering Research Centers program and assist the centers in achieving their stated goals.
- Stimulate effective use of institutional resources through industry/university collaboration in research and education and more synergistic interaction between the science and engineering communities.
- Assist in creating an environment in universities and industry in which new ideas and innovations can flourish.
- Help to eliminate institutional deficiencies by developing key concepts having catalytic effects in strengthening the educational and research base.
- Stimulate activities to identify new concepts and research directions.
- Support approaches, activities, and programs that encourage multidisciplinary research and create a knowledge base for systems approaches.
- Disseminate effectively the results of Foundation-sponsored research.
- Meet Foundation goals for support of research by minority and women engineers.

Organizational structure is one way in which an institution's program directions are manifested. Responding to the redefinition of its goals, the Directorate for Engineering reorganized its structure in late 1984 to accommodate the following groups of activities:

- chemical, biochemical, and thermal engineering
- mechanics, structures, and materials engineering
- electrical, communications, and systems engineering
- design, manufacturing, and computer engineering
- emerging and critical engineering systems
- cross-disciplinary engineering research centers

Table 1 presents more detail on the scope of activities in the six areas.

The list of directorate goals emphasizes the need for new directions and for change in some of the traditional patterns within the Directorate for Engineering. The reorganization of the directorate is accepted by the committee as a management mechanism for achieving objectives that we support.

The changes described above are occurring against the backdrop of NSF's history of support for high-quality individual work that produces, as well, the development of first-rate faculty and graduate students. As important as the actual research results may be, it is the educational process, in encouraging the development of thousands of outstanding people to pursue careers

TABLE 1 National Science Foundation Directorate for Engineering—New Structure

Division I Chemical, Biochemical, & Thermal Engineering	Division II Mechanics, Structures, & Materials Engineering	Division III Electrical, Communications, & Systems Engineering	Division IV Design, Manufacturing, & Computer Engineering	Division V Emerging & Critical Engineering Systems
Kinetics & Catalysis Engineering	Solid Mechanics	Quantum Electronics, Waves, Beams	Automation & System Integration	Section 1: Emerging Engineering Systems
Biochemical & Biomass Engineering	Structures & Building Systems	Solid State & Microstructures	Manufacturing Engineering Systems	Biotechnology
Process & Reaction Engineering	Fluid Dynamics & Hydraulics	Communications Systems & Information Theory	Computer Engineering (Software Technology & Engineering)	Bioengineering & Research to Aid the Handicapped
Multiphase Chemical Processing	Tribology	Systems Theory & Operations Research	Design Theory & Methodology	Lightwave Technology
Separation & Purification	Control Systems	Instrumentation, Sensing, & Measurement	Computer-Integrated Engineering	Section 2: Critical Engineering Systems
Thermodynamics & Transport Phenomena	Materials Engineering & Processing			Earthquake Hazard
Particulate & Solid Processes				Environmental Engineering
Thermal Systems & Engineering				Public Infrastructure
				Natural Hazards Mitigation

OFFICE OF CROSS-DISCIPLINARY RESEARCH

Engineering Research Centers

in research areas of engineering, that has yielded even greater benefit to our society. As the engineering directorate reorders its priorities to achieve new objectives in research, it is particularly important that its objectives with regard to training people in methods of research be advanced as well.

Any organizational structure adopted by the NSF Directorate for Engineering introduces the possibility that individual research proposals will not conform to organizational boundaries. Whereas in the previous organization this was a special problem for proposals relating to manufacturing and design, in the present organization the problem shifts to other fields. The committee therefore fully supports the management of the engineering directorate in its effort to ensure that project proposals need not be tailored to a particular NSF organizational unit, but that engineering directorate procedures be sufficiently flexible to accommodate proper consideration of all worthy projects designed to advance engineering science and technology. The committee urges frequent review to ensure that operations within the directorate meet this goal.

The major emphases in the new direction planned by the management of the Directorate for Engineering, as we understand them, are to develop more funding for quality basic research in nontraditional technologies and in emerging technologies of national importance, and also to encourage support for research in areas of potentially high leverage for the future. We endorse in principle these new emphases and believe that, when properly managed, they will indeed strengthen the engineering profession. This management will require diligence in order to maintain the historical strengths that have provided the traditions of quality individual research and human resource development, while giving appropriate emphasis to the new directions.

Moving into research areas such as the science base of design and manufacturing is riskier than supporting only traditional disciplinary areas. While some of the research in new areas may not prove fruitful, these are areas of the future and must be explored. The new areas of research are appropriate for NSF in these times of great change in engineering. We must not forget, however, our national responsibility to conduct the research required to accelerate the solution of such enduring problems as physical infrastructure decay and waste disposal.

High-quality research by first-rate individuals is, we believe, possible in the context of all the work supported by NSF, whether "top down" or "bottom up" in its formulation, that is, whether in response to NSF initiatives or to initiatives from individual principal investigators. In developing the "top down" directions, we would encourage NSF to make increased use of industry in defining and assessing those nontraditional and emerging technologies that are truly most important to our industrial competitiveness.

The criteria to be used in achieving an expansion of activities supported by the Directorate for Engineering must be prudently balanced. National needs, status of field, number of proposals of high quality, originality of proposals, and other factors all have a place. Maintaining the kind of diverse portfolio of projects that is always an asset in basic research while responding to the pressures that rightfully influence the engineering enterprise is a central and ongoing challenge of the directorate.

With these comments in mind, we stress the following areas where NSF has a critical national role in the engineering domain: (a) maintaining the strength and ensuring the continuing development of the engineering sciences; (b) developing basic understanding and methods in the processes of engineering, e.g., design, modeling, simulation, optimization, data processing, and systems integration; (c) serving the needs of society through strengthening the national system for education and research; (d) stimulating the development of curricula and personnel (especially Ph.D.s and faculty) in new as well as existing areas; and (e) serving as the natural spokesperson for engineering research just as it is for basic science.

Without addressing specifically the administrative means for implementation, we recommend that greatly increased emphasis be given to computer and information engineering. We are convinced that computer and information engineering represents today a major part of engineering research and practice and offers enormous potential for the future. The rapidly growing importance of computers in all areas of engineering and especially in computer-aided design and systems analysis calls for a greater role for computer and information engineering within NSF in general and in the engineering directorate in particular.

Within the National Science Foundation, support for computer-oriented research is dispersed, at present, among three divisions, each in a different directorate. The respective levels of support in FY 84 for computer-oriented research were as follows: Computer Research, $33.9 million; Information Science and Technology, $6.2 million; and Electrical Systems and Computer Engineering, $16.8 million. In the case of the last division, the level of support has increased from $8.5 million in FY 79 to $16.8 million in FY 84. New FY 86 initiatives to provide supercomputer access complicate the management of computer-related programs in NSF still further.

Viewed against the background of the increasingly crucial role played by computers in engineering, it is evident that current NSF engineering commitments for computer and information engineering still fall far short of what is needed. In the national interest, substantially larger resources will have to be allocated not only to the development of computers as tools for engineering design and analysis but also to the support of both basic and applied research on computer systems and their use in telecommunications, data storage and retrieval, robotics, manufacturing, and process control. The committee recommends that the NSF director evaluate the effectiveness of the present structure to deal with the magnitude and complexity of the computer issue.

ESTIMATING THE RESOURCE REQUIREMENTS

The committee was asked to estimate the funding level commensurate with a reasonable and appropriate strengthening of engineering research and education activities in NSF. As with all such studies and estimates, the committee offers several caveats. The time available for this study was short, and extensive and thorough new surveys were not possible. The figures that the committee suggests are intended to approximate the needs. More detailed study of the needs and interrelationships in academic engineering research and education would be required to permit more refined estimates of appropriate rates of growth and levels of expenditure.

The committee is mindful that recommendations on funding levels must be conditioned by the broad context of the total government funding for research and development in which the NSF programs must be planned. Even more important, it recognized, was the national context in which federal government spending proposals must be evaluated. The nation now has the largest federal budget deficit in its history; justification for mounting new federal efforts must therefore be especially cogent. In spite of the stringent budgetary actions proposed by the President in FY 86, the federal budget does reflect the conviction that important programs require significantly increased support. Engineering research in the NSF is one of those programs; the engineering directorate budget shows a growth of 13.3 percent. The committee welcomes this action.

With these considerations in mind, the committee examined various approaches to quantifying, in costs, the desirable level of increased engineering research and education effort in NSF consistent with general thrusts of the newly structured engineering effort of the Foundation.

In considering funding levels for engineering research and education in NSF, it is important that the mission of the Foundation in these fields be understood: briefly stated, it is to ensure the vigor of engineering research, principally in universities, and the associated educational needs. This mission is vital to the health of the national engineering and technological enterprise even though the NSF funding is relatively modest within the context of the total federal governmental effort. (As previously noted, NSF contributes about 11 percent of the total federal government funding of engineering research and development in colleges and universities.) Other agencies of the government such as the Department of Defense, the National Aeronautics and Space Administration, and the Department of Energy collectively play a larger financial role, but in general the work supported by these agencies is more narrowly focused on their mission objectives.

In fact NSF holds the central federal responsibility for strengthening engineering research and education in universities because no other governmental institution has the basic charter to strengthen engineering research and education. Because of its unique role, the policies of NSF in support of engineering are critical in shaping university programs.

Approaches to quantifying desirable funding increases can take many forms. In particular, we examined four different types of arguments.

1. National needs arguments postulate national needs that can be met in whole or in part by increased federal investment in engineering research and education. For example, there is widespread national concern for the international competitiveness of U.S. industry. Such competitiveness in large part depends directly on technological innovation and on the technological leadership that underpins it. The requirements of national defense are similarly often cited in justification of engineering research.

2. Opportunity arguments take the view that from time to time fields of engineering and technology become ripe for rapid development or offer new opportunities for exploiting new engineering and scientific concepts. Such opportunities have been opened up by breakthroughs in computer technology, lasers, electron microscopy, and nuclear magnetic resonance technology, to cite several examples.

3. Capacity arguments stress that an increase in the productivity of the engineering enterprise can be achieved efficiently by making fuller use of the unused capacity that exists in academic institutions to conduct engineering research and to provide educational opportunities. A parallel argument relates to the capacity of the general population to produce people capable of acquiring the education needed to meet national demands for engineers and for engineering faculty.

4. Comparability arguments justify funding increases on the basis of comparisons with funding in related or analogous fields, seeking to demonstrate that one field is underfunded in comparison with other fields. Such arguments are based on premises about the proper role of government in supporting the research undergirding various sectors of society, for example, the health and the manufacturing industries.

All of these modes of argument are relevant in estimating funding needs. However, arguments based upon comparability and capacity principles are insufficient in themselves, and are important only in the presence of arguments related to national needs or engineering opportunities.

The committee first identified national needs that would require increases for support of engineering research and education. The committee believes that the challenge to U.S. industrial competitiveness and leadership over the past two decades emphasizes an urgent need for intensified efforts to strengthen the nation's engineering and technological capabilities. The underlying long-term challenge before us is manifest in the severe economic competition from other nations that the United States is facing, the weakening of domestic support for the U.S. technology base in some industrial sectors (for example, minerals, where several industrial laboratories have closed down), critical shortcomings in engineering education, and unplanned and undesirable impacts from some applications of technology.

Among all of the factors bearing upon industrial competitiveness, superior technology is one of our best opportunities. U.S. technology has excelled uniformly in the past, excels only in certain industries in the present, and must again excel more generally in the future if we are to meet the international challenge. The maintenance of this country's technological leadership cannot be assured in the absence of engineering research at the cutting edge of knowledge. Because the process of technological innovation depends directly upon the quality and quantity of the engineering and technological talent available in this nation, it is vital that NSF regard this national challenge as a challenge to itself as an agency and, more specifically, to its engineering directorate.

The restructuring of the programmatic directions of the Directorate for Engineering is fully consistent with a strong role for NSF in helping the nation address its industrial competitiveness problems. The potential for such a role is the principal argument for this committee's recommending accelerated support of engineering research and education within NSF.

The committee sought to develop an approach to estimating the financial resources required to enable the National Science

Foundation to meet its responsibilities for a healthy engineering research and educational establishment within the United States in the competitive years ahead. In addressing this question, the committee was mindful that there are now widely perceived needs for a strengthened U.S. engineering research effort. These have been expressed by the National Science Board,[10] the National Academy of Engineering,[1] the Congress,[11] and advisory groups to the President.[5,12] President Reagan himself, in the State of the Union address (February 7, 1985), stressed the potential for technology to increase productivity and competitiveness and the administration's plans to seek record funding for research and development.

In examining the range of criteria relevant to estimating required resources based on these national needs, the members of this committee concluded that an engineering research and education effort must be adequate to meet manpower objectives, secure a fundamental understanding of the processes related to engineering systems, advance engineering methodology across a broad spectrum relevant to societal and industrial needs, foster innovation, and capitalize on new science and new techniques. We agree with others that engineering research and education are keys to answering challenges to U.S. leadership in areas of recent success such as computers, materials, and flight and space technology. They are no less important in areas where U.S. leadership has already been seriously eroded under competition from abroad. Several older industrial sectors that involve processing, manufacturing, and construction, for example, have fallen far behind at great social cost in terms of unemployment and displacement. Further, a strong engineering research community is essential if we are to reap the benefits of advances in newly opening areas such as biotechnology and laser optics and if we are to make progress on public domain issues such as handling of hazardous wastes, sustainable use of resources, and mitigation of natural hazards, where fundamental research may sometimes be neglected.

In the judgment of the committee, it would be a serious mistake for the United States to abandon its effort to compete internationally in whole sectors of the economy, such as basic metals, transportation vehicles, or electronics, and NSF should not in any event presume to make such national policies. The objectives of the Foundation should be to stimulate and support engineering education and research of high quality that undergirds all of industrial technology.

Shifting its attention from the consideration of national needs to "opportunity arguments" for engineering research, the committee considered those newly emerging opportunities for engineering research and education that might suggest the wisdom of an increased investment now. The rapid growth in information systems caused by the revolutionary development in integrated circuits which led to inexpensive computing power has dramatically altered the way engineering is done. The ability to send vast amounts of information at very high bit rates by optical fiber systems is having a great impact on how we do business and spend our leisure time. Enormous improvements in measurement capacity have been introduced through new developments in such fields as electron microscopy and nuclear magnetic resonance. The increased sophistication and greater efficiency of our instrumentation, computation, and data processing make fundamental engineering work more relevant to practice than ever before, opening up vistas of high-technology engineering practice, which as a nation we have only begun to appreciate and utilize. The opportunities lie not only in new fields but also in transformation of traditional fields such as the design and management phases of construction engineering.

Taking advantage of these opportunities will be possible only if the nation can develop the talent that will enable our industrial and governmental institutions to remain dynamic and innovative, which will mean focusing on the development of a larger number of U.S. students in the graduate engineering education system. The opportunity to do so is now present and has been perceived by our young people, both men and women. Full of enthusiasm for participation in the excitement and professional rewards of the current technological revolution, they have enrolled at universities in record high numbers in undergraduate engineering. Not only have their numbers increased dramatically in the last decade, but their intellectual caliber and motivation are impressive by all the conventional measures of place in high school class, SAT scores, and so forth. These young people represent a pool of talent from which a greatly expanded research capability can be developed. In other words, we have the human and intellectual capacity to expand our national technical capability. But this will require adequate financial support and facilities for engineering research and graduate education at universities. We have an opportunity now to balance the short-term gains available to young U.S. engineering graduates with incentives to pursue Ph.D. degrees and research careers that are likely to be highly beneficial to the nation in the long run.

The committee attempted to assess whether the capacity of the academic institutions doing engineering research was being fully used. We found the record mixed. Some members of the committee expressed the view that at a small number of leading engineering institutions the faculty was fully and properly occupied and the capacity to take on additional students or research activities was limited unless faculty, funding, and facilities were increased. Members of the committee also pointed out that many of the engineering schools in this country were so committed to undergraduate teaching that they might not be operating most effectively in performing their mission of research and instruction at both graduate and undergraduate levels. In such institutions scarce faculty resources are simultaneously overworked and underutilized.

It was also evident that the capacity to undertake additional engineering research within the limits of existing faculty, equipment, and facilities varies among fields of engineering research. Electrical and electronic engineering and related computer engineering are short on capacity, while some engineering fields have significant additional capacity if funds become available.

Regarding the increase in student populations at engineering schools, statistics available to the committee showed that undergraduate engineering enrollment has increased dramatically over the past 10 years, and that at present the engineering educational system is maintaining a rough balance between supply and demand for graduates at the bachelor's level in all fields except in electronics and computer engineering, where shortages persist.[1,12]

The problem of providing outstanding talent exists principally at graduate levels. We noted the well-publicized statistics about the percentage of foreign-born graduate students in U.S. engineering schools. Broadly speaking, more than half of engineering Ph.D. degrees are being awarded to foreign nationals; in the stricter sense of awards to students holding temporary visas, over the three-year period 1981-1983, 27 percent of master's degrees and 39 percent of doctorates in engineering in the United States were awarded to foreign nationals. The committee's assessment is that while the training of foreign-born students has many values for the United States, the training of domestic students in advanced engineering is far below the level essential to meet national goals.

After considering the four kinds of arguments that help to quantify required budget increases, the committee considered the several areas of engineering expenditure within the responsibility of NSF. In the following sections we address the subject of resource allocations by focusing on four general areas of engineering activity within the NSF engineering directorate:[14]

1. basic engineering sciences
2. research for design, manufacturing, and computer engineering
3. research for critical and emerging technologies
4. Engineering Research Centers program

We then examine two cross-cutting issues that need to be addressed and that are central to the funding issues enumerated above. These are:

1. experimental equipment, instrumentation, and other facilities; and
2. human resources.

ENGINEERING SCIENCE PROGRAM RESOURCE REQUIREMENTS

The basic engineering sciences are fundamental areas of study developed especially for their relevance to technological advances across a broad spectrum of engineering. They include such topics as thermodynamics and transport, chemical kinetics, solid-state and materials science, fluid and solid mechanics, dynamics and control, electronics, and communication theory, among others. These are currently the major areas of NSF involvement with engineering research. These essential, challenging areas in which investigators seek an understanding of basic phenomena, in some ways analogous to the science areas supported in other parts of NSF, are pursued in ways that are important to the fundamental methodology for engineering application.

The direct results of such research are often important, and the participation of students in its conduct yields the corollary and perhaps more important benefit of advanced training essential to the development of the talent required by the engineering and technological enterprise in this country. Support for these research areas in universities is, in fact, one of the principal means of meeting significant educational goals in engineering. While keeping faculty members probing (and able to convey) the frontiers of understanding in their fields, it provides the graduate students involved with exposure to rigorous methods and the landscape of research.

Support by NSF for basic engineering science research is, in the opinion of the committee, not commensurate with NSF's responsibilities in this area. The late 1970s and 1980s have been years of modest growth for the Foundation (see Table 2). While engineering research funding kept pace with this modest growth, new engineering subjects have opened, in remarkable ways, and available engineering research funds have had to be spread ever more thinly. The net result has been a lack of significant growth in basic engineering research areas.

TABLE 2 Actual NSF Obligations by Fiscal Year, FY 79 to FY 84

	FY 79	FY 80	FY 81	FY 82	FY 83	FY 84
Directorate for Engineering ($ million)	72	77	85	93	102	119
Increase (percent)		6.9	10.4	9.4	9.7	16.7
Total NSF ($ million)	911	975	1,022	995	1,093	1,322
Increase (percent)		7.0	4.8	–2.6	9.8	21.0

SOURCE: National Science Foundation, Directorate for Engineering.

Further, the low level of past NSF support for acquisition and maintenance of experimental equipment has prevented many of the engineering science areas from moving ahead as rapidly as might be possible with the best instrumentation and equipment. Many graduate students involved in engineering research, for example in metallurgy and several other fields of materials engineering, simply do not see and work with the types of equipment defining the forefront of modern work. It must be understood that not only does the academic engineering science community lack modern equipment, but it also lacks funds and even a tradition for funding the corps of technicians necessary to maintain world-class, modern, high-technology research programs.

In short, we are not doing as well as we can and should in the crucial foundation areas for engineering research. This has unfortunate consequences for the overall health of the U.S. engineering effort and for the preparation that can be given to graduate students. The level of support for the basic engineering science divisions in the Directorate for Engineering is approximately $78 million in FY 85 and approximately $80 million are being requested in the President's budget for FY 86. This represents an increase over two years of 7.5 percent over the approximately $74 million allotted to the same area in FY 84.[20] The level of funding is incommensurate with the problem, and such increases will continue to leave major unmet needs.

RESOURCES FOR DESIGN, MANUFACTURING, AND COMPUTER ENGINEERING

As mentioned earlier, the committee supports the policy directions implied by the new structure of the Directorate for Engineering. We believe that the basic engineering science programs at NSF must be complemented by programs that focus on broad, integrated engineering studies critical to industrial productivity. Representative of such work are basic research projects related to computers, manufacturing, design, modeling, optimization, and systems integration. To a greater extent than in the past, such projects will entail close collaboration with industry and will also require the acquisition of relatively expensive equipment and instrumentation. Exposure of students to research of this type should provide a valuable supplement to their foundation in engineering sciences, making them more appreciative and willing to respond to the demands they are likely to face in their careers. One of the purposes of the Engineering Research Centers (ERC) program is to provide for some of this exposure to students. But the ERC program alone will not be sufficient.

We note that the FY 85 budget for design, manufacturing, and computer engineering in the engineering directorate is a modest $17 million, with the expectation of healthy growth in the immediate future (to more than $20 million requested for FY 86). Indeed, the committee believes that the arguments of national need and opportunity are so compelling that this sector of the budget should grow rapidly, within the limits of effective management. Because the base is so small the budget for this program can be expected to grow quite dramatically for a few years before settling down to growth rates planned for the rest of the directorate.

RESOURCES FOR CRITICAL AND EMERGING TECHNOLOGIES

Along with the directorate's effort in support of engineering research for design, processing, and manufacturing is its allied, major new initiative in support of programs for emerging technologies, combined with a program directed at critical technologies. The emerging-technology focus is new for NSF, and its potential for stimulating the development of talented individuals and a sound body of expertise in important new areas is great. In pursuing both programs, it will be important to budget the efforts and to make decisions about investigators so that program managers responsible for this area of the directorate stay in close and continuous interaction with those fostering fundamental engineering research.

The critical technologies, as defined for the committee by NSF, focus on the underlying aspects of problems that are generally deemed to be the responsibility of the government to address or regulate, such as infrastructure support and mitigation of natural and man-made hazards. The NSF effort in earthquake hazards research is a good example; fundamental research on waste management is another.

We note that $35 million have been allocated for critical and emerging technologies in the FY 85 budget, and $38 million are requested in the President's budget for FY 86. Because of the newness of some of these initiatives we believe that NSF should proceed deliberately, choosing only a few technologies for major, focused effort so that some sense of the success of the concept of supporting critical and emerging technologies can be obtained before plunging into additional areas. Research applied to modern technology is expensive even when carefully targeted. If the effort is as successful as the NSF leadership anticipates, these activities represent opportunities that would warrant dramatic growth.

RESOURCES FOR ENGINEERING RESEARCH CENTERS

The Engineering Research Centers (ERC) program has just been initiated. The National Academy of Engineering advised NSF on this program earlier, suggesting that the program should grow to embrace 25 centers at a total cost of $100 million per year, excluding stipends for students.[2] The committee has been informed that 142 proposals were submitted by universities in response to a solicitation by the Foundation. Approximately 40 of these proposals were judged to be of such high quality that they should eventually be funded, with 14 selected for the final round of competition; however, the NSF budget permitted only 6 of these highly qualified finalist proposals to be funded in the first year of the program. Clearly, the interest in ERCs in both the academic and industrial community is strong, as are the proposals for carrying out this program.

The committee recognizes that these centers are a new response to the nation's engineering research and education needs, and experience with the program will be needed to judge whether it should go beyond the level of $100 million per year. Progression from $10 million in FY 85 to $25 million in FY 86 is a fair beginning. If the impact of ERCs on student education bears out the hopes of NSF and NAE, this program should yield both research results and talent development in industrially significant topics, justifying continued rapid growth.

The committee would like to encourage NSF not to abandon the support of industry/university efforts smaller in scope and funding than those contemplated for the engineering research centers. Intermediate-sized awards for two to four faculty members interacting with one or more industrial laboratories on more limited topics can help fill the gap between the large engineering research centers and the typical NSF grants in engineering of $60,000 to $70,000. The newly proposed Materials Research Groups of the NSF Division of Materials Research are illustrative of approaches to support of projects on an intermediate scale.[15]

CROSS-CUTTING ISSUES--A BASIS FOR FUNDING ESTIMATES

Experimental Equipment, Instrumentation, and Other Facilities

The first major cross-cutting issue that requires immediate attention by NSF involves the need for up-to-date experimental equipment and instrumentation, which are key requirements both for carrying out good research and for educating good engineers; they are required in all the programs described above. The needs for and costs of such equipment and instrumentation have been growing rapidly because of the changes and advances in technology over the last few decades. Most of the modern techniques and instruments incorporate sophisticated microprocessors, sensors, and controls, and permit new levels of quality in engineering research and practice. Specifically, needs range from those for advanced spectroscopy, nuclear magnetic resonance of solid materials, surface analysis techniques, molecular beam epitaxy for artificially structured materials, feedback-controlled mechanical testing, high-speed photography, and laser-based instrumentation such as laser velocimetry and other combustion diagnostics, to needs for more technologically oriented equipment such as engine dynamometers, metal-forming equipment, paint-spray equipment, air pollution measuring equipment, ultra-high-speed machining facilities, and the systems for flexible manufacturing.

In NSF's national survey of academic research instruments and instrumentation needs of the 157 largest R&D colleges and universities, 91 percent of engineering departments reported important subject areas in which critical experiments cannot be performed because of lack of needed equipment.[16] The adequacy of only about 10 percent of the instrumentation in engineering was judged to be excellent, and the adequacy of more than half was judged to be insufficient.

In the first year of the new DOD equipment awards program (FY 83), approximately 2,500 proposals were received, requesting a total of more than $645 million. In response, 200 awards totaling $30 million went to 80 universities for research equipment in science and engineering. There is an enormous unmet need.

The magnitude of the task is so great that the precision of any estimate becomes less important than the development of a strategy to distribute responsibility for its execution. A program of steady replacement and development from many sources is preferable to a large outlay from a single source followed by a period of neglect. Clearly, the responsibility for equipment, instrumentation, and facilities is shared by many federal agencies, universities themselves, state governments, and industry as well.

The responsibility of the NSF engineering directorate clearly includes the provision of equipment and instrumentation for university research in engineering. NSF has been supporting acquisition of 27 percent of academic research instrument systems in use over a range of fields and 16 percent in engineering (Table 3). NSF may wish to consider ways to maximize the benefit/cost ratio for research equipment; for example, in some areas it may be preferable to concentrate large investments in universities willing to maintain facilities accessible to others in academia and in industry. Associated usage fees can help maintain such facilities once established.

NSF may prefer to use other channels, such as a Foundation-wide Instructional Equipment Fund, to meet the substantial and critical needs for equipment and instrumentation in <u>instructional</u> laboratories in science and engineering. A detailed, 1982 survey of combined laboratory and teaching equipment needs of 10 state-supported colleges of engineering in Texas showed a total need of $99 million, of which $37 million was judged critical. A similar study in Pennsylvania revealed a $75-million need for instructional equipment alone. Requirements at the national level can only be estimated, but the scale of the problem is obvious. Needs for instructional equipment are especially urgent in engineering because of the importance of bachelor's and master's degrees in the engineering profession.

Several innovative ways of funding capital budgets have been proposed for NSF in recent years, and the needs on campus for equipment and instrumentation in engineering further stress the urgency of developing these new modes.

In seeking to define the scope of NSF in the provision of engineering equipment and instrumentation, the committee noted that in fields such as physics and chemistry it has been traditional in NSF to include significant funding for costly major items of research equipment. In physics, for example, the amount for the acquisition of major items of equipment (items costing more than

TABLE 3 Acquisition of Academic Research Instrument Systems in Use, by Field and Source of Funds: National Estimates, 1982[a]

Principal Field of Research Use	Percent of Aggregate Acquisition Cost,[b] by Funding Source									
	Federal						Nonfederal			
	Total	NSF	NIH	DOD	DOE	Other	Univ.	State	Industry	Other[c]
Total	100%	27%	4%	14%	7%	6%	29%	5%	4%	5%
Physical sciences, total	100	34	5	9	9	8	27	2	1	5
Chemistry	100	36	9	4	3	2	37	3	2	5
Physics and astronomy	100	31	1	16	17	16	14	0	0	5
Engineering, total	100	16	1	22	6	4	36	6	6	3
Electrical	100	21	3	38	6	2	21	2	5	2
Mechanical	100	16	0	27	6	2	29	4	11	5
Metallurgical/materials	100	18	0	6	11	9	26	18	6	6
Chemical	100	26	1	25	5	5	24	4	8	1
Civil	100	12	0	1	3	2	62	10	5	4
Other[d]	100	7	2	16	5	3	60	3	2	2
Computer science	100	22	1	17	0	3	27	11	17	2
Materials science	100	41	2	16	10	4	16	8	2	0
Interdisciplinary, other	100	24	9	13	4	4	22	8	4	13

NOTE: Sum of percents may not equal 100 because of rounding.

[a]Statistical estimates refer to research instrument systems (including all dedicated accessories and components) originally costing \$10,000-\$1 million in physical science, engineering, and computer science departments and facilities at the 157 largest R&D colleges and universities in the United States. Estimates limited to systems used for research in 1982. Sample size = 2,582 systems.
[b]Actual cost to acquire instrument system at this university, including transportation and construction/labor costs.
[c]Individuals and nonprofit organizations.
[d]E.g., aerospace, agricultural, biomedical, industrial, nuclear, systems.

SOURCE: Reference 16.

$100,000) is about 14 percent of the total funding available for physics research ($17 million out of $123 million budgeted in FY 86).

We have been able to find only modest funding within the budget of the Directorate for Engineering for such equipment (in FY 85, less than $1 million out of $142 million), although in 1982 about 40 percent of the aggregate purchase cost of all academic engineering research instrument systems was in a system cost range of $75,000 to $1 million. In such critical areas as catalysis, composite materials, and interfaces in semiconductor materials, a whole series of instruments for surface analysis--with each instrument costing more than $250,000--is required. It would be appropriate for the Directorate for Engineering to be more responsive to the evident needs for major equipment.

Because of the technological advances of recent years, engineering schools now need equipment in areas where they have done very little research in the past. Thus, in many cases it will be necessary to provide new equipment without the benefit of previous acquisitions. This is true, for example, in robotics and process engineering, not to mention facilities for such activities as ultraclean microelectronics fabrication. In order to fill the vacuum in academic activities in these areas, the funds required from NSF for equipment, instrumentation, and facilities for engineering research will be significant. Meanwhile, only 18 percent of the instrument systems in active research use in academic engineering in 1982 were judged to be state of the art.[16] These active research instrument systems were assessed to have a replacement value in 1982 of $413 million.[16]

The analysis that follows does not cover funding for renovation and new construction of facilities, although the committee recognized that funding for such space is an urgent need. It is our assumption that facilities questions will be addressed largely outside the framework of the NSF engineering directorate. The committee urges continuing attention to this issue by an agency with overarching national responsibility, such as the Office of Science and Technology Policy.

The committee postulated a scenario for modernization of research equipment in engineering schools based on the condition of existing instrumentation and consistent with the doubling of the doctoral student population described later in this report. It attempted a logistical estimate of the needs over a five-year period. We suggest that the 82 percent not regarded as "state of the art" of existing equipment assessed at $413 million in 1982 ought to be replaced, at a cost exceeding the $340 million in 1982 replacement costs. Noting again that 91 percent of the 157 largest engineering colleges report critical areas of activity in which the <u>absence</u> of equipment precludes research, and recognizing that a million-dollar investment in each of these schools would ameliorate but not solve this problem, we see the need for another $150-million investment. Finally, we note that the anticipated doubling of the doctoral population also implies a substantial increase in equipment and instrument needs, perhaps increasing the costs by 50 percent. Thus, the total estimated cost of modernizing and augmenting the equipment and instrumentation for academic engineering would be about $750 million in 1982 dollars (or, approaching $900 million in 1985 dollars). In contrast, actual national expenditure for purchase of research equipment for engineering in FY 82 was $90.9 million.[16]

In assessing the overall national need, we must recognize that the problem assessed so carefully in 1982 continues to grow because of continuing obsolescence of equipment, and this growth will persist even as we begin to address the problem. These factors push our assessment of the magnitude of the problem into the billion-dollar range, a range consistent with the results of detailed analysis of one school. The College of Engineering of the University of Texas at Austin, which graduated between 2 and 3 percent of engineering Ph.D.s in the United States between 1976 and 1980,[17] estimated in 1984 that its total need for research equipment exceeded $36 million and that its critical equipment needs exceeded $14 million.[18]

As noted earlier, NSF has been supporting only about 16 percent of the total cost of instrument acquisition for academic engineering research. The committee used this percentage as a measure of the minimum responsibility of NSF for equipment and instrumentation. In fact, we believe the share of the responsibility borne by NSF should be significantly higher than 16 percent--closer to the 34 percent allocated in the physical sciences. But, using this 16 percent share, we can calculate a required fund for capital equipment for the five-year period of about $160 million. This translates into an average of $32 million per year, or, more likely, a graduated program reaching a level of $40 or $50 million. We urge NSF to work with other federal agencies in developing plans to address the capital needs of the U.S. academic research enterprise.[19]

The committee recognizes that the assumptions forming the basis of its estimates can be altered to yield other scenarios. We believe, however, that these are reasonable estimates for the funding of equipment and instrumentation to support a much-strengthened engineering research and education effort on the part of NSF. By adopting in its analysis a 16 percent share of the overall responsibility for NSF in instrument acquisition in engineering, the committee does not mean to fix that figure. And, again, we have not treated the questions of refurbishing existing facilities and constructing new facilities, nor the need for instructional equipment; we have considered here only research equipment and instrumentation.

Human Resources

As indicated earlier in this report, a central goal for engineering in this country must be the development of more Ph.D.-level engineering talent. In achieving this goal, a larger percentage of graduate students must be U.S. citizens or foreign-born students planning permanent residence in the United States. This requires a major strengthening of opportunities for graduate engineering education. While the need is for graduate students of all kinds, the committee focused on the need for Ph.D. engineers.

As noted previously, the ratio of Ph.D. degrees to B.S. degrees in engineering fell from 8 percent to 4 percent between 1973 and 1983. In terms of human capabilities, the former figure is presumably achievable once again. This means that we have the potential as a nation to double the rate of production of engineering Ph.D.s, which currently number about 3,000 per year. Although demand predictions in this field are notoriously difficult, the evidence suggests that this goal is not inconsistent with current projections.

Support for graduate students can be achieved through fellowship programs and entrainment of students into engineering research efforts. For young researchers who have recently received their Ph.D.s, NSF's Presidential Young Investigator (PYI) program has been a major step in encouraging young people to pursue research careers on science and engineering faculties. Approximately half of these awards now go to those interested in engineering. We believe that the present ratio is reasonable, while noting that (according to the original plan) in the steady state after FY 89, this could require $30 million annually from the NSF engineering directorate budget for 500 Presidential Young Investigators, in contrast with the roughly $6 million scheduled for FY 85. The funds necessary for this expansion should come from budget augmentations, not from displacements of research contracts awarded by proposal review.

In past years there have been other kinds of fellowship programs in NSF. While these largely have been abandoned with the shift of government-support philosophy from education and knowledge generation to research acquisition, we believe that NSF should increase its support for the NSF Graduate Research Fellowship Program, currently (FY 85) at about $27 million. Individual awards for engineering students must also increase to cover educational expenses plus a stipend approaching half of the competing salary offered to B.S. degree recipients, so that these fellowships will attract students receiving B.S. degrees in the United States.[3] The cost for such programs would be modest, especially if fellowships are limited to two-year periods with research assistantship support to follow. If each of 100 universities admitted 10 such NSF fellows each year across the range of science and engineering disciplines so that in the steady state the national population of NSF fellows reached 2,000, the impact on the national supply of science and engineering Ph.D.s would be significant but well within the capacity of our educational system. If we assume the full costs of a fellowship year to be about $25,000, the annual cost would probably range around $50 million, of which half should be invested in engineering (following the Presidential Young Investigators model).

A midcareer program for upgrading engineering faculty by providing time for them to acquire broader expertise, especially to work effectively in emerging technology areas in industry and research universities, would also be important. Such a program would contribute especially to the universities that do not have substantial research programs but are in fact responsible for educating the majority of our engineers. Remaining current in an engineering career is perceived as a major problem in industry. Increased university/industry cooperation could perhaps benefit both academic and industry engineers in this regard.

Traditionally in NSF, fellowship programs have been managed and budgeted outside of the research directorates, and that model has been assumed in the calculation here of future budget requirements of the Directorate for Engineering. In other agencies, for example the National Institutes of Health, research and fellowship programs are managed jointly, and that model may be appropriate for NSF.

The principal means of increasing the engineering Ph.D. output, however, is through research grants and contracts to engineering schools that will provide the support and work environment for them. The committee used a simple model of an engineering research unit built around one faculty member as a basis for its estimates. Each faculty member would have a team of four graduate students (perhaps two master's-degree-level students, and two Ph.D. students), and either one technician or one postdoctoral student. Depending on the seniority of the faculty member, institutional support of academic-year salary, tuition costs, overhead, and other factors, support for such a unit would cost between $150,000 and $250,000 per year, exclusive of the equipment, instrumentation, and space that would be needed.

We envision such engineering research units being expanded in significant numbers to increase the annual output of Ph.D.s. If it were determined on the basis of additional studies (such as that of the Committee on Education and Utilization of the Engineer) that a doubling of the present Ph.D. output of 3,000 per year over a five-year period were called for, as would follow from a return to 8 percent of B.S. degrees leading to Ph.D. degrees (assuming no further growth in B.S. degrees), and if NSF were responsible for continuing to fund its current share of 20 percent of engineering Ph.D.s through increases in the traditional research grants, then at the end of five years the NSF budget would need to increase for this purpose by an amount between $90 million and $150 million, assuming that one Ph.D. degree is awarded to a member of an engineering research unit each year. The support of the units should, of course, be spread over activities in each of the divisions of the engineering directorate. Increases in engineering Ph.D. production can also be expected from the operations of the ERCs, and this would modestly raise the 20 percent share of engineering Ph.D.s funded by the NSF.

SUMMARY OF FUNDING ESTIMATES

The committee concludes that a significant and consistent funding increase will be required if the opportunities for capitalizing on new scientific and engineering developments are to be seized and the nation is to address seriously the national need to train essential advanced engineering talent. We propose the development of separate, coordinated plans for addressing operating and capital needs.

If we hold aside the question of equipment and instrumentation and focus on the needs related to the ERCs and human resources (including the PYI program), our estimates represent an expansion of the budget of the NSF Directorate for Engineering from the present $142 million through the $170 million requested by the President in FY 86 to somewhere between approximately $350 million and $410 million, or between 2 and 3 times the present size over a five-year period.

At the same time there should be developed a capital plan for engineering equipment and instrumentation aimed at attaining an average level of NSF support of more than $30 million per year for five years. Given the likely path of graduated increases in equipment funding, the combined operating and capital budgets for the NSF engineering directorate five years hence would be in the range of $380 to $440 million (Table 4). We recognize that there will be support for equipment and instrumentation included in funds budgeted for the ERCs, and we welcome such support as an increase in the share of this national responsibility for research equipment borne by NSF. We also stress the need for other federal agencies to move forward vigorously to meet the needs in the area of engineering research equipment.

The committee recognizes that expansion of the NSF engineering directorate program and increased support for engineering research and education by other agencies will require additional space in research institutions. We have not been able to estimate such costs, nor are we in a position to postulate what the NSF role

TABLE 4 Estimated NSF Annual Resource Requirements for Directorate for Engineering by FY 90 (constant 1985 dollars)

Requirement	Amount (in millions)
FY 85 Directorate for Engineering budget	$142
New operating requirements	
Engineering Research Centers[a]	90
Research programs[b]	90 to 150
Presidential Young Investigator program	24
Capital equipment program[c]	33
Total	380 to 440[d]

[a]Assumes increase in program from $10 million to $100 million per year.
[b]Funding for research grants in engineering directorate divisions; based on human resource needs.
[c]Assumes increase from current expenditure of $17 million to $50 million in fifth year of five-year, $160-million program.
[d]Rounded; does not include graduate and midcareer research fellowships, instructional equipment, facilities, and other aspects of NSF engineering effort not budgeted in the engineering directorate.

should be. We suggest that this critical issue be addressed by an agency charged with broader responsibility than the NSF Directorate for Engineering.

Another important and related activity that currently lies outside the domain of the NSF engineering directorate, and therefore perhaps beyond the purview of this committee, is the NSF Graduate Research Fellowship Program. The committee finds it impossible to separate national objectives in research and graduate education, and it bases its estimate of needs for research support on the assumption that graduate fellowship budgets also will grow substantially, reaching approximately $25 million annually in engineering. In the absence of such growth in fellowship support, the national objectives would require an even larger investment in funded research.

In conclusion, an aggressive growth rate can bring the National Science Foundation to the level necessary to meet its responsibilities for the health of engineering research and education under the assumptions the committee has used. Recruiting outstanding staff to NSF to lead such an ambitious program will be a major constraint, and the rate at which the augmentation occurs will of course need to be modulated by the total requirements for various federal investments. The engineering directorate and its programs will need to compete with other claims on the NSF dollar. The case for significant increases will need to be made forcefully and convincingly by the Directorate for Engineering. We believe that the case is a powerful one and that an augmented program will serve the national interest by enhancing our industrial competitiveness.

NOTES

1. National Academy of Engineering. Strengthening Engineering in the National Science Foundation. National Academy of Engineering, Washington, D.C., 1983.
2. Guidelines for Engineering Research Centers. National Academy of Engineering, Washington, D.C., 1984.
3. Engineering Education and Practice in the United States: Foundations of Our Techno-Economic Future. Report of the National Research Council Committee on Education and Utilization of the Engineer. National Academy Press, Washington, D.C., 1985.
4. The Imperative for Excellence. Report of the White House Science Council Panel on the Health of the Universities and Colleges (Packard-Bromley Committee). In press.
5. The Second Term. Report from the Business-Higher Education Forum. 1985.
6. See Science Resources Studies. Estimates of R&D Expenditures, National Science Foundation, Washington, D.C., 1984.
7. Throughout this report the FY 85 budget of the NSF engineering directorate is accepted at its original level of $142 million, despite the midyear additions through program transfers from other NSF directorates.
8. Three major facilities initiated prior to FY 85 are being continued. These are the National Research and Resource Facility for submicron structures at Cornell University, the Geotechnical Centrifuge Facility at NASA-Ames, and the Fluidization Bed Facilities at West Virginia University.
9. Presented by NSF staff to the NAE Ad Hoc Committee to Evaluate the Programs of the NSF Directorate for Engineering, December 13-14, 1984.
10. Statement on the Engineering Mission of the NSF over the Next Decade, as adopted by the National Science Board at its 246th meeting on August 18-19, 1983, NSB-83-250. National Science Foundation, Washington, D.C.

11. See, for example, Targeting the Process of Innovation: An Agenda for U.S. Technological Leadership and Industrial Competitiveness. Steering Committee of the Task Force on High Technology Initiatives. House Republican Research Committee, U.S. House of Representatives, May 1984.
12. Global Competition: The New Reality. President's Commission on Industrial Competitiveness. John A. Young, Chairman. White House, Washington, D.C., 1985.
13. Office of Science and Engineering Personnel. Labor Market Conditions for Engineers. National Academy Press, Washington, D.C., 1984.
14. We have organized our assessments along lines parallel to the groupings of activities recently put into effect in the reorganization of the NSF Directorate for Engineering.
15. See National Research Council's 1984 report, Major Facilities for Materials Research and Related Disciplines, for many examples of topics that might be pursued in this way.
16. Division of Science Resources Studies. Academic Research Equipment in the Physical and Computer Sciences and Engineering. National Science Foundation, Washington, D.C., 1984.
17. National Research Council. Assessment of Research-Doctorate Programs in the United States: Engineering. National Academy Press, Washington, D.C., 1982.
18. A Six-year Plan for the College of Engineering. College of Engineering of the University of Texas at Austin, 1985.
19. See National Science Board. Academic Science and Engineering Physical Infrastructure. The Bridge, Vol. 14, No. 3, 1984, p. 23.
20. It should be noted that the proposed increase between FY 85 and FY 86 for single-investigator projects over all engineering directorate divisions is about 10 percent.