Scanning the Issue

Engineering Research Centers: Goals and Results

I. Driving Forces for the ERC Program

The Engineering Research Centers (ERC) Program was created in 1985 to meet a national need to improve engineering research and education, focusing them more directly on speeding the contribution of engineering research to industry and enhancing the ability of engineering graduates to contribute to the industrial competitiveness of the United States. At that time, the nation's engineering leadership had come to realize that while U.S. engineering faculty had made great strides in basing modern engineering on advanced scientific knowledge and the latest laboratory and computational tools, sufficient emphasis had not been placed on the contributions that knowledge could make to technological advancement. Nor had there been appropriate focus on design and manufacturing to keep pace with increasingly sophisticated industrial rivals around the world.

A good deal of engineering research in academe had come to be modeled after the reductionist approach of the sciences and engineering science. While engineering science is vital to the health of engineering, the research foundations upon which engineering and technological advances are based cannot stop with discovery and analysis, which are the research paradigms fundamental to science. In order to advance technology and manufacturing processes, engineering research must take on the additional dimensions of synthesis and integration needed to understand and advance technology and engineering systems.

In addition, industry had found that graduates from engineering schools were to immersed in the single-discipline focus of their professors, unfamiliar with technology and the integrative approaches needed to advance technological systems. New entrants had to be taught how to work in teams and how to depend upon the paradigms of other research disciplines needed to make incremental advances in production systems and develop new products.

These trends were the driving forces that led to the creation of the Engineering Research Centers Program. The major goals for the program were developed in 1984 by a National Academy of Engineering panel of engineering leaders from industry and academe chaired by Dale Compton then a Vice President for Research with the Ford Motor Co.[1] The ERC Program began operation in the same year.

II. Goals and Features of ERC's

The goal of the Engineering Research Centers Program is to couple and focus engineering and scientific disciplines on technological systems competitiveness of U.S. industry. The Program establishes major centers involving a three-way partnership among academia, industry, and the Federal and State levels of government.

All ERC's share the following key features:

- A clear and coherent vision of a next-generation technological advance in an engineering system critical to U.S. industrial competitiveness.
- A strategic research plan focused of critical advances in knowledge, tools, and technologies needed to fulfill the vision of the center.
- A cross-disciplinary team of engineers and scientists, involved in work that spans the research spectrum from analysis and synthesis, through design and processing, to proof-of-concept experimentation in testbeds.
- Involvement of industry in the planning, research, and education programs to focus the ERC on long-term, generic needs of the industry, while at the same time improving the transfer of knowledge and technological advances to industrial and other users.
- An educational program involving significant numbers of graduate and undergraduate students in research teams focused on technological systems with exposure to industrial views.
- Development of curricular and course-material advances based on the unique perspective of the ERC, focused on students and practitioners.
- Major or specialized experimental capabilities supported by a large-scale contemporary instrumentation and laboratory infrastructure.

These key features provide the ERC's with complex challenges but each is free to experiment with different means to meet these challenges. In collaboration with industry, the ERC's are building a new intellectual culture

[1] W. Dale Compton, *Guidelines for Engineering Research Centers, A Report for the National Science Foundation*, National Academy of Engineering, Washington, D.C. 1984.

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across the disciplines to advance engineering research, education, and technology.

NSF's support per year ranges from $1,900,000 to $3,300,000. These funds are leveraged, on average by a factor of two from non-NSF sources. NSF provides 30% of the ERCs' annual support, while industry provides another 30%, and the remainder comes from other federal agencies, the states, and the universities. An important factor for the success of a center is to have support from the university that provides the space and facilities and promotes policies which will facilitate cross-disciplinary collaboration and reward interdisciplinary, team research focused on knowledge and technological advancement.

NSF's support for an ERC has a potential life span of 11 years, depending on the quality of its strategic plans and resulting progress over time. ERCs are free to compete for support beyond 11 years in any announced ERC competition. The ERC Program has a system of oversight and evaluation that consists of annual reports and reviews of progress and plans. In addition, in the third and sixth year of operation, an ERC faces a major evaluation of its progress and plans. If the ERC is not performing at a high level, it is phased out over a two-year period.

The program has initiated 21 ERC's since 1985; there are currently 18 ERC's, since three were phased out as a result of their third-year evaluations. The total budget for the program in NY 1992 is $47,300,000. The current set of centers focuses on design and manufacturing, materials processing for manufacturing, optoelectronics/microelectronics/telecommunications, biotechnology/bioengineering, energy and resource recover, and the civil infrastructure.[2]

III. Innovations Resulting from the ERC Challenge

The ERC concept provides a major challenge to universities and industry. The difficult task of setting up a center takes about three years and it takes six or more years to attain full momentum and productivity. The centers have had to develop many creative approaches to research management, education, and technology transfer to meet these challenges.

A. Strategic Planning

One innovation, strategic planning for targeted fundamental research, arose from concerns raised to the ERC Program management at NSF by the industrial advisors to the individual ERC's were beginning to look like collections of projects. Integrating the projects and focusing them on common goals was harder to achieve in an academic environment than was realized.

Industry posed the following challenge to the management of the program:

> "What are the ERC's going to deliver? Students and papers? We can already get that with the way we fund research now. The ERC's have to be focused on 'deliverables'."

The ERC Program staff considered this challenge and initiated a requirement for the ERC's to develop strategic research plans to focus their research programs on knowledge and technological advances, the research-based "deliverables" of an ERC. The strategic plans are developed in collaboration with the industrial advisors to the ERC's. They are a major innovation in academic research.

Traditionally, research projects originated from avenues of inquiry generated by individual investigators or in response to a particular problem posed by an industrial sponsor. In contrast, the strategic plans put a fundamental new twist on a research program directing it to "strategic" knowledge creation. They focus on long-term advances, plan for intermediate demonstrations of concepts in experimental testbeds to explore ideas along the way, and serve as road maps for identifying and integrating projects necessary to move toward the needed advances. The strategic plans involve a combination of science or knowledge-driven and technology-driven research. They are flexible and evolutionary allowing industry and academe to explore technological options, with the luxury of the possibility of success and failure. Both avenues lead to greater understanding of needed advances.

B. Engineering Systems

Another critical component of ERC's, which sets these centers apart from others, is their focus on engineering systems. ERC's are unique in this dimension because their scope and cross-disciplinary nature affords them the ability to tackle an engineering system as a whole, rather than the bits and pieces of disciplinary inquiry that make up much of research in academe. Systems integrate components to serve a processing function or product need. Some of the engineering systems that are being explored in the current set of ERC's include a knowledge-based design modeling system for rapid prototyping; a wide-band optical telecommunications network that integrates signal transmission control system with voice, data, and image presentation systems, a deep-ocean tension-leg platform for offshore recovery of oil in deep water; and next-generation magnetic or magneto-optic data storage systems that optimize head/media interface to achieve higher rates of data storage.

C. Research Testbeds

Demonstration of engineering concepts in research testbeds is critical to ERC's as they move the work along the R&D continuum from analysis through synthesis to integration in an experimental demonstration of a concept. Engineering is an integrative effort and it needs to be focused on manifestation of systems in testbeds to determine their feasibility and utility. In the ERC's, these testbeds range from the multichamber process module cluster in which multiple processing steps are carried out *in situ*, with low thermal budget single-wafer processing techniques at the ERC for Advanced Electronic Materials Processing at North Carolina State University, to the Quick

[2] The individual centers are listed at the end of this introduction.

Turnaround Cell at the Purdue Intelligent Manufacturing Systems ERC, which integrates design, machining, and inspection in a manufacturing cell developed for flexible, small-batch manufacturing.

IV. Industrial Involement and Technology Transfer

Industry is actively involved in the ERC's. In 1991, over 480 firms secured a total of almost 700 memberships in the set of 18 ERC's; 10 firms hold memberships in more than one ERC. Thirty percent are small business and 13% are foreign owned. All the firms provide 30% of the total support of the ERC's.

The ERC's have developed a wide range of activities to meet the challenge of involving industry in their research and education programs in order to speed the transfer of advances to industry and to improve the next generation of practicing engineers. Central to the concept of an ERC is the concept of integrating industrial views in planning, research, and education. This is technology transfer, though not in a sense of a "handoff" to industry of an advance made by academics. Rather, it is more interactive, where faculty, students, and industrial personnel work together over a long period of time, both expanding and shaping their views of research and technology based on the views and perspectives of the others. The ERC's gain input from their industrial partners to help shape their strategic plans based on industrial views of generic problems driving industrial research and technological advancement. Industry brings real-world problems and processing and manufacturing constraints. Industrial firms gain a longer term view of possibilities based on research supported by a cadre of students and faculty working in teams, supported by individual work, that spans the disciplinary paradigms.

Advances made in an ERC pass through various theoretical and experimental phases, ranging from exploration of potential, to technical feasibility demonstration in a testbed. Some advances are moved along further through focused joint projects supported by one firm or a consortia of firms to test and explore the concept, moving them even closer to development. Once an idea moves near entry into the proprietary realm of a firm's process or products, it is the time for industry to pick up the responsibility.

A very important means of technology transfer is the informal and frequent interaction of people from the two sectors. Most of the centers have industrial residence programs that involve industrial personnel in the research and education programs of the center for extended periods, ranging from a few weeks or months to several years. These individuals work cooperatively with faculty and students in research, they mentor students, develop special courses or design or competitions, and teach. In other cases, center faculty members and students work on-site at industrial research facilities for a day, a week, or a summer.

It is this day-to-day involvement of individuals from industry and academe that is the most effective means of technology transfer. Ideas move quickly across the sectors, industrial sponsors become "advocates" for new developments based on their experience in the centers, and graduates of the centers move into positions in industry where they can demonstrate their unique experience with engineering systems. Industry hires ERC graduates to bring the new perspective into their firms.

The centers have moved a wide range of advances to use in industry. This transfer is in the form of either hardware or software. Examples of ERC-developed hardware include photonic disk drives and switches, an implantable cardiac defibrillator, a new type of scanning tunneling electron microscope, a bridge corrosion monitoring device, an environmentally friendly polyurethane foam, instruments for monitoring biofouling, and a new system for implanting a protective ion coating on material surfaces. Software products include many expert systems, models, and algorithms to improve processes and operations in fields ranging from combustion, to intelligent manufacturing, to integrated circuit design and manufacturing, and optoelectronic telecommunications.[3]

V. Education

The educational dimension of the ERC's was designed to integrate research and education, involve undergraduate as well as graduate students in research, and expose these students to industrial views, cross-disciplinary teamwork, and engineering systems.

By design, the ERC's involve both undergraduate and graduate students. At the time of the initiation of the program, the idea of involving undergraduate students in research was considered an innovation. The purpose was to expose these students to the excitement of research and to involve them with industry. In this way, whether they choose to go to work in industry after the undergraduate degree, as many do in engineering, or choose to continue on to graduate studies, they would have the benefit of cross-disciplinary teamwork in collaboration with industry. These undergraduate students have proven so capable and productive that the faculty now encourage their involvement in the centers. One ERC, the Center for Interfacial Engineering at the University of Minnesota, developed an innovative program through which undergraduates carry out research projects on-site at small businesses. Over the years, we have seen that the ERC undergraduate students gain insights into the world of research and industry that help them make more effective career choices and contribute more effectively wherever they choose to go.

The unique feature of an ERC education for graduate students is that it enables them to work on the engineering systems and testbeds where they learn the integrative aspects of engineering, necessary in engineering practice; and they learn to depend on the work of their teammates in order to complete a project. Many of these students work freely across the disciplines, readily drawing on the expertise of faculty and students from a wide range of

[3] *Highlights of Engineering Research Centers Technology Transfer*, Engineering Centers Division, National Science Foundation, NSF 92-6.

fields. Students are exposed to industrial view of research through their involvement with industrial residents, on-site research in forms, presentations to industrial visitors, and their industrial mentors, etc.

The ERC program was designed to provide this type of experience for students in order to improve their effectiveness in industry and bring them up to speed more quickly. The industrial sponsors of the ERC's indicate that they find these features of ERC students especially valuable.

ERC's have also taken the lead to develop innovations in engineering curricula based on their unique environments. The Biotechnology Process Engineering Center at MIT has initiated an interdepartmental biotechnology Ph.D. program which draws students from disciplinary degree programs in biology, chemistry, and chemical engineering to train them in aspects of biotechnology and bioprocess engineering. Other special degree programs are an industrially oriented MS program in Systems Engineering at the University of Maryland/Harvard University's Systems ERC, an MS program in Manufacturing at Purdue University introduced from the experiences gained from the Intelligent Manufacturing Systems ERC at Purdue University

Finally, since industry and the Nation are concerned that the engineering profession broaden its base of participants to include more women, members of ethnic and racial groups currently underrepresented, and persons with disabilities in engineering, the ERC's have developed outreach programs with other schools to expand the exposure of these groups to engineering.

VI. Center Directors—A New Cadre of Academic Research Managers

Over the years, the leadership and management challenges posed by the ERC concept have produced a new type of academic research manager. There is a new cadre of faculty with a long-term vision for the interface of research and technology, capable of strategic research planning, who are experienced in collaborating with industry. They can manage large, complex cross-disciplinary teams of individuals to focus their work along the research continuum from basic inquiry to experimental testing in proof-of-concept testbeds. They also have shown that the integration of research and education strengthens the student and the faculty. They have created research and educational environment in which a new generation of faculty is growing to professional maturity, capable of working on engineering systems with industry.

VII. Summary

In the eight years since the inception of the ERC Program, it has been demonstrated that it is possible to develop centers that meet the challenging and innovative concepts in research and education encompassed by the program's goals. These centers have worked in collaboration with industry to make the ERC concept a dynamic and evolutionary response to the needs of industry and the country. They provide the country with a small set of highly innovative centers, focused on strategic knowledge creation, leading to innovations in technology and education, and producing students and faculty capable of leading the country in its quest for increased competitiveness.

The papers that follow in this special issue are specific examples of how these challenges are being met in the centers that focus on the electronic and optoelectronic industries.

The following is a list and a brief description of all the current Engineering Research Centers. Those described more fully in the papers in this issue are so noted.

Engineering Research Centers Currently Supported by NSF:

Advanced Manufacturing Design and Systems

- **Engineering Design Research** at *Carnegie-Mellon University.*
  The research program of the center is focused on advanced design methodologies to drastically reduce the design-to product cycle and to build flexible, domain-independent design environments to integrate quantitative and qualitative methods for design optimization. The research program is organized into three "laboratories": Design for Manufacturing, Synthesis, and Design Systems. Director: Friedrich B. (Fritz) Prinz. Telephone: 412–268–3372. The research of this center is described in the first paper in this issue.
- **Systems Research** at the *University of Maryland and Harvard University.*
  The research program of the center is focused on integrating design of advanced and complex automation and information systems. The goal is to create a computer-aided design environment that can achieve complete integration from conceptual development to technology selection, hardware implementation, testing and validation. The research thrusts are: intelligent servo-mechanisms, chemical process systems, manufacturing systems, and systems integration. Center Director: Steven I. Marcus. Telephone: 301–405–7589
- **Computational Field Simulation** at *Mississippi State University.*
  The research program at the center is focused on improved design tools for simulating the response of engineered systems in their physical surroundings, concentrating on fluid flow, heat and mass transfer, and electromagnetics, essential in many engineered applications including engines, aircraft, ships processing systems, and oil exploration. The research thrusts are: solution algorithms, grid generation, scientific visualization, system software, computer architecture, and rapid prototyping. Center Director: Joe F. Thompson. Telephone: 601–325–3560
- **Net Shape Manufacturing** at the *Ohio State University.*
  The research program of the center focuses on cost-effective manufacture of discrete parts, spanning all the stages of manufacturing from engineering mate-

rials to finished or near-finished dimensions by melt processing, shaping from powder, forming from sheet, and forming from billet. The research thrusts are: design and manufacturing, billet forming, sheet forming, polymer processing, and die casting. Center Director: Taylan Altan. Telephone: 614–292–5063

- **Intelligent Manufacturing Systems** at *Purdue University*.
  The research program of the center focuses on discrete manufacturing systems with the capability to respond quickly and correctly to changing requirements. The research thrusts are: process models, design tools and integrated systems. Center Director: James J. Solberg. Telephone: 317–494–7715. The research of this center is described in the second paper in this issue.

Advanced Materials Processing

- **Interfacial Engineering** at the *University of Minnesota*
  The research program of the center is focused on molecular interactions at the interface or boundary between two materials. The research thrusts are: thin-film processing, coating processes, polymer microstructures, surfactancy and self-assembly processes, and biomedical interfacial engineering. Center Director: D. Fennell Evans. Telephone: 612–625–6828
- **Advanced Electronic Materials Processing** at *North Carolina Institutions*
  The research program of the center is focused on developing multichamber process module clusters and to demonstrate their advantage for automated single-wafer processing over conventional processing techniques. The research thrusts are: module development and system integration, plasma processing, thermal and optical processing, materials analysis and characterization, and device development. Center Director: Nino Masnari. Telephone: 919–515–3001. The research of this center is described in the third paper in this issue.
- **Plasma-Aided Manufacturing** at the *University of Wisconsin-Madison and the University of Minnesota*
  The research program of the center is focused on exploring new plasma processes that produce advanced materials and products of importance to manufacturing and generating fundamental control strategies that can be utilized for manufacturing. The research thrusts are: plasma etching and microwave processing, plasma deposition and polymerization, plasma synthesis, sintering, and spraying of high-technology ceramics and refractory materials, and plasma modification of materials. Center Director: J. Leon Shohet. Telephone: 608–262–1191. The research of this center is described in the fourth paper in this issue.

Biotechnology/Bioengineering

- **Emerging Cardiovascular Technologies** at *Duke University and other North Carolina Institutions*
  The research program of the center is focused on creating the basic knowledge needed to design and produce a new generation of advanced biomedical systems, devices, and instruments for cardiac interventional systems and cardiovascular imaging systems. The research thrusts are: antiarrhythmic systems, real time 3–D ultrasonic imaging, magnetic resonance microscopy, and sensors and stents. Telephone: 919–660–5137. The research of this center is described in the fifth paper in this issue.
- **Biotechnology Process Engineering** at the *Massachusetts Institute of Technology*
  The research program of the center is focused on integrating the life sciences, chemistry and engineering to produce advanced manufacturing technologies. The research thrusts are: engineering and scientific principles in protein production and process engineering and science in therapeutic protein purification. Center Director: Daniel I.C. Wang. Telephone: 617–253–2504.
- **Interfacial Microbial Process Engineering** at *Montana State University*
  The research program of the center is focused on understanding and controlling the growth and adhesion of microscopic organisms to the infrastructure of various systems, such as water treatment, oil refining, heating and cooling systems, food processing, etc. The research thrusts are: transport and interfacial transfer phenomena, physiological ecology, and genetic transfer, extracellular chemical and electrochemical phenomena, instrumentation and process control, and modeling and information management. Acting Center Director: John Sears. Telephone: 406–994–4770.

Construction and Infrastructure

- **Advanced Technology for Large Structural Systems** at *Lehigh University*
  The research program of the center is focused on the design, construction and service performance of large structural systems. The research thrusts are: in-service monitoring and control technology, durability/longevity of infrastructure, knowledge of complete structural systems, connections, automated construction tools, systems methodology for design, and computer integration of design and construction. Center Director: John W. Fisher. Telephone: 217–333–3097

Energy and Resources Recovery

- **Advanced Combustion Engineering Research** at *Brigham Young University and the University of Utah.*
  The research program of the center is focused on developing advanced combustion control technologies that lead to improved combustion or conversion processes. The research thrusts are: fuel structure and reaction mechanisms, fuel minerals, fouling and slagging, pollution formation and control and hazardous-waste incineration, turbulent, reacting fluid mechanics and heat transfer, and comprehensive model development. Center Director: L. Douglas Smoot. Telephone: 810–378–4326
- **Offshore Technology** at *University of Texas at Austin.*
  The research program of the center is focused on developing the fundamental engineering knowledge

critical to the exploitation of deep ocean resources, with emphasis on deep water petroleum resources. The research thrusts are: fluid/structures interactions, integrity of materials and structural systems, structures/sea floor interactions. Center Director: Richard Seymour. Telephone: 409–845–7252

Optoelectronics, Microelectronics, and Telecommunications

- **Data Storage Systems** at *Carnegie-Mellon University* The research program of the center is focused on efficiently integrating storage systems into high-performance computing environments, and high-density magnetic and magneto-optic disk and tape recording systems. The research thrusts are: storage and computer systems integration, magnetic recording technology, magnetic-optic recording technology, and electronic subsystems. Center Director: Mark Kryder. Telephone: 412–268–6600.
- **Optoelectronic Computing Systems** at the *University of Colorado and Colorado State University.*
  The research program of the center is focused on expanding the intellectual foundations of optoelectronic computing systems and devices and demonstrating their use in proof-of-principle machines. The research thrusts are: optical connections, digital optical computer, optical signal processing, and materials and devices. Center Director: W. Thomas Cathey. Telephone: 303–492–7967. The research of this center is described in the sixth paper in this issue.
- **Telecommunications Research** at *Columbia University.*
  The research program of the center is focused on integrated telecommunications networks for high-speed multimedia information movement and management using three underlying core technologies: VLSI, lightwave networks, network management and control and broadband applications. Center Director: Anthony Acampora. Telephone: 212–854–3123. The research of this center is described in the seventh paper in this issue.
- **Compound Semiconductor Microelectronics** at the *University of Illinois, Urbana-Champaign.*
  The research program of the center is focused on the development of the engineering science and technology base for fabrication of optoelectronic integrated circuits and their application in optical interconnect systems. The research thrusts are: systems design and analysis, transmitters/waveguides/modulators, optoelectronic integrated receivers, and supporting technologies. Center Director: Stephen Bishop. Telephone: 217–333–3097. The research of this center is described in the eight paper in this issue.

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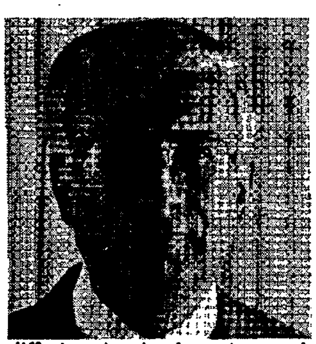

Richard B. Fair (Fellow, IEEE) *was born in Los Angeles, CA, on September 12, 1942. He received the B.S.E.E. degree from Duke University in Durham, NC, in 1964, the M.S.E.E. degree from the Pennsylvania State University, University Park, in 1966, and the Ph.D. degree from Duke University and an NDEA Fellowship whole doing graduate work at Duke.*

In 1969 he joined the Semiconductor Device Laboratory, Bell Laboratories, Reading, PA. As a member of the technical staff, his primary responsibilities were in the areas of processing and modeling of both unipolar and bipolar transistors. In 1973, he became Supervisor of the Semiconductor Device Development Group. He has had responsibility for the development of power transistors, IMPATT diodes, and other microwave devices, as well as MOS technology and IC design. He currently holds appointments as a Professor of Electrical Engineering at Duke University, and Vice President of MCNC and Executive Director of its Center for Microelectronics. He has authored over 95 refereed journal articles, eight book chapters, and has given over 85 invited talks at conferences in the areas of impurity diffusion, ion implantation, and device physics.

Dr. Fair is listed in the 1973 edition of Outstanding Young Men of America *and was voted an Outstanding Young Electrical Engin r for 1974 by Eta Kappa Nu. He was Chairman of the Solid-State Device Committee for the 1977 IEDM and has served on the Integrated Circuit Technology Subcommittee. He was a Symposium Cochairman at the 1984 MRS meeting in Boston and has served as a member of the Electronic Materials Committee of the Metallurgical Society of the AIME and the Electronics Division Executive Committee of the Electrochemical Society. Currently, he is a member of the Editorial Board of the* PROCEEDINGS OF THE IEEE *and is an Associate Editor for the* TRANSACTIONS ON ELECTRON DEVICES. *He is listed in the American Men and Woman in Science, Who's Who in Technology Today, Who's Who in Engineering, and Who's Who in America; and is a member of the Electrochemical Society and Sigma Xi.*

Lynn Preston *is the Deputy Director of the Engineering Education and Centers Division of the Directorate for Engineering at the National Science Foundation (NSF). Her efforts at NSF have focused interdisciplinary research on technological advancement in collaboration with industry. She came to NSF in the early 1970s to serve in the Research Applied to National Needs Program and became a Deputy Division Director, focusing her efforts on the development of new programs important for societal problems and technological advancement. In the early 1980s, while managing the NSF-wide Office of Interdisciplinary research, she developed various initiatives that lead NSF to focus on emerging technologies. She organized a joint effort across biology, engineering, and chemistry to focus NSF's resources on biotechnology resulting in a major new initiative. In addition, she also helped to organize the then-nascent fields of biochemical engineering, magnetics for data storage, and lightwave technology.*

She was one of the initiators of the Engineering Research Center's program and ha managed the program since inception. She helped develop the early conceptual framework for the Science and Technology Research Center's Program and the New Industry/University Cooperative Research Center's Program. Currently, she serves as the Chair of an NSF team devoted to developing a long-term strategy for improving collaboration among NSF, academe, and industry.

Ms. Preston has an advanced degree in economics from the University of Colorado at Boulder. Her earlier career was focused on local economic development efforts in rural Thailand with the Battelle Memorial Institute in Bangkok, Thailand, and macroeconomic modeling and labor force modeling with the Institute for Defense Analyses in Arlington, VA.