The Engineering Research Centers: Leaders in Change

The Engineering Research Centers: Leaders in Change /

Order from
National Technical
Information Service,
Springfield, Va.
22161
Order No. PB87-187217

Cross-Disciplinary Engineering Research Committee
Commission on Engineering and Technical Systems
National Research Council (U.S.).

National Academy Press
Washington, D.C. 1987

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

This activity was supported by the National Science Foundation under cooperative agreement No. ENG-8505051 between the Foundation and the National Academy of Sciences. The opinions, findings, and conclusions or recommendations are those of the Workshop Steering Group and the speakers and do not necessarily reflect the views of the National Science Foundation.

Copies of this report may be obtained from:

National Academy Press
2101 Constitution Ave., NW
Washington, DC 20418

A charge of $3.00 for postage and handling is required. Supplies are limited.

Report No.: CETS-CROSS-6

ID #
8-11-87

CROSS-DISCIPLINARY ENGINEERING RESEARCH COMMITTEE

DON E. KASH, George Lynn Cross Research Professor, Science and Public Policy Program, The University of Oklahoma (*Chairman*)

JOHN A. ARMSTRONG, Director of Research, IBM Corporation

ROBERT R. FOSSUM, Dean, School of Engineering and Applied Science, Southern Methodist University

WILLIAM C. HITTINGER, Executive Vice-President, RCA Corporation (Retired)

ARTHUR E. HUMPHREY, Director, Biotechnology Center, Lehigh University

JAMES F. LARDNER, Vice-President, Component Group, Deere & Company

ALBERT R. C. WESTWOOD, Corporate Director, Research and Development, Martin Marietta Corporation

JOHN H. WIGGINS, Research Engineer, D.B.A.

Staff

KERSTIN B. POLLACK, *Director, Cross-Disciplinary Engineering Research Committee*

COURTLAND S. LEWIS, *Consultant/Writer*

VERNA J. BOWEN, *Administrative Assistant*

Preface

The Engineering Research Centers (ERCs) program has come a remarkably long way in a very short time. The concept itself was conceived less than three years ago, and already there are 11 ERCs situated around the nation and across the breadth of engineering research. Furthermore, each of these Centers is moving very quickly to establish a vigorous program of cross-disciplinary research and education within its area of interest. The ERCs are the vanguard of a new approach to meeting the serious challenges to the nation's industrial competitiveness.

The symposium "The Engineering Research Centers: Leaders in Change" was held under the auspices of the National Research Council's Commission on Engineering and Technical Systems (CETS). The Cross-Disciplinary Engineering Research Committee, which organized and hosted the symposium, is a unit of CETS that supports the National Science Foundation's Division of Cross-Disciplinary Research (sponsor of the ERC program). We, the members of the Symposium Steering Group, are pleased to be part of the significant experiment that the ERCs represent.

Symposium Steering Group
DON E. KASH, *Chairman*
JOHN A. ARMSTRONG
ROBERT R. FOSSUM
WILLIAM C. HITTINGER
ARTHUR E. HUMPHREY
JAMES F. LARDNER
ALBERT R. C. WESTWOOD
JOHN H. WIGGINS

Contents

III Industrial Interaction and Perspectives

IV ERCs and the State Governments

The Engineering Research Centers: Leaders in Change

Summary

The Engineering Research Centers (ERCs) program has generated almost unprecedented interest throughout the nation's engineering community. The symposium titled "The Engineering Research Centers: Leaders in Change" was the second symposium held to communicate the activities and progress of the ERCs. Nearly 400 representatives from universities, industry, and government at every level came to hear speakers describe the Centers and discuss many aspects of their operation and their goals. Discussion was encouraged, so the symposium became the forum for a lively interchange of ideas about the ERCs and, indeed, about the present and future status of the engineering research and development enterprise in the United States. (The discussion that followed various presentations is summarized immediately after each paper.)

The keynote address was given by John M. McTague, vice-president for research of the Ford Motor Company and former director of the Office of Science and Technology Policy. McTague discussed the ERC program as an idea whose time has come and explored their relation to the future of U.S. industrial competitiveness. Nam P. Suh, assistant director of the National Science Foundation (NSF), picked up this theme, focusing on the lessons that NSF has learned during the first year of the program. Next, the directors of the first six Centers described the development of their research and education programs, their programs of interaction with industry, the development of their support base and facilities, and overall operational experience with their Centers. A number of speakers examined, from different points of view, the problems, opportunities, and strategies for success entailed in building industrial involvement in centers like the ERCs. Of particular interest was a panel discussion of these matters by representatives of the ERCs, government, and industry. Two speakers representing state governments described their states' technology-development initiatives and mechanisms for supporting research centers with an applied focus.

In the concluding session of the symposium the five newly established ERCs were introduced. The five Center directors described their varied plans and programs in support of research, education, and industrial liaison, as well as the organizational structure of the Center. The new ERCs showed an impressive diversity of ideas and initiatives in the pursuit of excellence in their areas of emphasis.

Together with the six Centers established earlier, the 11 Centers now in existence comprise a broad-based and powerful attack on key areas of cross-disciplinary research that are certain to be central to the nation's technological future. It is a base that NSF intends to continue expanding year by year as its budget permits. There is evidence of ample interest by universities in the expansion of the program: In the first two years a total of 244 proposals were received, with requests for support totaling $3.5 billion. Other government agencies, both federal and state, have begun or plan to establish similar university-based research programs. An important theme of the symposium was that collaborative efforts among industry, government, and academe are essential to re-establishing and maintaining U.S. technological leadership. The ERCs have been designed for just this purpose; they are rapidly becoming, as Nam Suh termed them, "models of the will to win in technology."

Speaker after speaker pointed to the gathering momentum of technology development efforts by other nations around the world and the increasing sophistication of those efforts. As Bruce Merrifield points out, a decade ago the United States was generating some 75 percent of the world's technology; now that figure has dropped to about 55 percent. The pace of change is such that we cannot rely on old forms and traditional structures to help us meet the challenge effectively. We must, as John McTague urges, "rededicate ourselves to change" if we are to regain and hold leadership in technology. He notes that one of the perils of leadership is that the strategy for staying ahead requires far more vision and determination than do the tactics for catching up.

The ERCs are designed to fit such a strategy. NSF Director Erich Bloch refers to them explicitly as "our answer to Japanese industrial targeting." With their emphasis on industrial interaction and research on problems of industrial relevance, with their cross-disciplinary focus and aggressive programs of technology transfer, the Centers are bringing a cultural change—what James Solberg terms "a quiet revolution"—to university campuses. They face considerable obstacles to their success, structural as well as attitudinal; the process of overcoming those obstacles *is* the process of changing the campus culture.

The change in culture is needed not only in universities but also in industry and government. Innovation today is an organizational product, a group product. Each of these sectors must emphasize collaborative teams and interdisciplinary activities focused on ultimate goals that have clear economic relevance. The enthusiastic industry support for the ERCs is one sign that U.S. industry already recognizes the value of the kind of culture that the Centers represent. In their first year of operation the ERCs received $13 million in cash and equipment from industry, exceeding the $10 million outlay by NSF. And that support came not just in the form of money and hardware; industrial firms sent their personnel to the campuses for extended periods of collaborative research with Center faculty. Delaware's industry interns and Purdue's on-site representatives are examples of a substantial commitment of human as well as financial resources. Industry interest in the ERCs has been very strong. In a single month, for example, 389 industry representatives toured the facilities of the ERC at Purdue.

Many state and local governments also perceive the crucial nature of the technological competition, and the changes in attitudes and practices needed to succeed in it. For them, the competition is not only international but regional, among states and among localities. The desire to secure jobs and a high standard of living for their citizens is the primary motivation behind state and local programs to stimulate technology development (just as it is, ultimately, for the federal government). State initiatives like

Pennsylvania's Ben Franklin Partnership and Ohio's Thomas Edison Program have contributed more than $450 million over the past three years in support of applied research. While the models and approaches used vary considerably, like the ERC program all of them emphasize the importance of new partnerships among business, higher education, and government.

Making those partnerships work requires flexibility and creativity. Governments and industry alike must be clear about the goals of the research programs they support; too often there is a mismatch between the near-term needs of the funding organizations and the long-range view that university research must take. An example of how these conflicting objectives may be reconciled is seen in the Center at the University of California, Santa Barbara, where a "clinic" approach to cooperative research on robotic systems is employed to develop actual systems while fundamental knowledge accrues continually as a by-product. James Solberg describes the shared, long-range systems view as a "distant beacon" that focuses the efforts of researchers while those efforts are being directed at shorter-range, problem-driven objectives. Michael Wozny emphasizes that the pursuit of research with "transitionable" (as distinct from specifically deliverable) results is a prerequisite for a successful Center.

Many of the speakers identified other characteristics or approaches that can lead to successful partnerships and facilitate the needed cultural changes. They include:

- The presence of "champions," or strong advocates, within the participating organizations.
- A strong and diverse research program, defined in terms of demonstrable cases with bounded milestones and with clear long-range implications and importance.
- Frequent and extensive contact between industrial and Center personnel.
- Strong commitment to the Center on the part of the university.
- Participation by the funding organizations in setting the Center's overall goals and appraising the research program objectives and progress.
- Effective mechanisms for transferring technology.

- Production of highly capable engineers who have a strong sense of industry's objectives, operations, and working environment.

These are useful guidelines; they are not rules—nor is the list complete. A central theme of the symposium was that the ERCs represent an experiment. They are the leading edge of a new approach to solving the problem of staying competitive in an age of rapid change. Part of that problem lies in the uncertainties with which it is bounded. We do not know what technologies will be crucial in the future. Investing in research is, therefore, necessarily a long-range gamble, the outcome of which will not be known for many years. It is important not to structure too thoroughly the way that the experiment is conducted. Nevertheless, it is essential to pursue the experiment, to make that gamble, and to face squarely what may be, in Nam Suh's words, "the greatest challenge we have faced since World War II."

Part I

LEADERSHIP FOR CHANGE

Introduction

ROBERT M. WHITE

It is now widely accepted that the United States faces an unprecedented international challenge to its industrial competitiveness. We see evidence of this fact throughout industry. There are many factors that affect the competitiveness of U.S. industry. In the short term, macroeconomic factors play a major role. Over the longer term, however, the ability of the United States to remain industrially competitive depends on two fundamentals: the state of our technology and the training of scientific and engineering talent. The latter may be the most important product of our universities in terms of the long-range impact on our national competitiveness.

The Engineering Research Centers are a response to this challenge. They represent an innovative institutional form and process. The Centers bring together the capabilities and resources of the government, universities, and industry. As cross-disciplinary engineering centers they can address the kinds of engineering and technological problems that are important to industry over the long term. As institutions located on campuses, they are intended to have a major impact on our educational system. In partnership with industry they can be responsive to long-term industrial issues.

This volume will describe the experiences of the Engineering Research Centers that have already been established, as well as the plans of those that are just being inaugurated. I hope that the papers presented in this volume, and the symposium on which it is based, will generate a useful exchange of information among the various groups participating in the work of the Engineering Research Centers, one that can lead to their strengthening.

The two institutions in the U.S. government that have been principally responsible for the launching of the Engineering Research Centers have been the Office of Science and Technology Policy and the National Science Foundation, under the leadership of Jay Keyworth, John McTague, Erich Bloch, and Nam Suh. The keynote of this volume is struck by John McTague in the next paper.

Engineering Research Centers: An Idea Whose Time Has Come

JOHN P. MCTAGUE

Several months ago, when I was asked to participate in the symposium on which this volume is based, I gladly accepted. Clearly, I was invited because of my position then as acting science advisor to the president. My predecessor, Jay Keyworth, played a major role in the birth of the Engineering Research Centers (ERCs) Program as an exemplar of the president's commitment to strengthening government-university-industry cooperation to improve U.S. economic competitiveness. In fact, one of my first tasks upon arriving at the White House Science Office was to participate in the budget process that led to the implementation of the first six ERCs.

Before I discuss the ERCs, I would like to say a word about my recent job change. Leaving the administration to enter the private sector was not a decision I made lightly or quickly. It was a rare privilege to be involved in the formulation of federal science and technology policy, especially the redirection of federal efforts toward the most vital aspect of scientific and technical advance—namely, basic research. But there comes a time for all of us in government when we should return to the real world to practice what we have preached—and, in particular, to live with the policies we have helped to create. So, after a few years of preaching to others about the importance of technology for economic competitiveness and about the necessity to increase government-industry-university partnerships, I am now forced to decide whether I really want to practice what I have been preaching.

When I made public my intention to resign from the White House Science Office, I naturally cancelled all speaking engagements related to that office. But when the organizers of the symposium generously renewed that invitation, I gladly accepted, for several reasons. First, it gave me the chance to spend an extra day in Washington with my family! Second, it was an occasion to re-examine from my new perspective my attitudes concerning government-university-industry cooperation in general and the ERCs in particular. And, third, in some sense I am personally linked to the ERCs by the fact that my predecessors in both my previous and present jobs played key roles in the early stages of the ERC concept. When Dale Compton was at Ford, he chaired the Academy committee that drafted the original guidelines for the Engineering Research Centers.*

Most of the readers of this volume are aware of the origins and outlines of the ERC concept and the federal government's strong support of these Centers, so I will not dwell on those familiar topics. In later papers in this volume the accomplishments of the six existing Centers and the plans for the new Centers will be presented, so I will leave it to others to discuss those subjects. Instead I would like to step back from the technical details of the ERCs and try to place them in the broader context of our nation's pursuit of scientific and industrial excellence. Since I have worked in both the university community and government, and now once again in industry, I may have something of an ecumenical perspective on the role the Centers can play. I would like to share that perspective.

First, it is eminently obvious that the ERC concept is important. The large turnout for the symposium (The Engineering Research Centers: Leaders in Change) attests to the high degree of interest on the part of researchers and administrators in industry, academe, and government. Even more concrete evidence has come from the avalanche of requests for ERC Program Announcements

---

* National Academy of Engineering. 1983. *Guidelines for Engineering Research Centers.*

(the National Science Foundation's request for proposals). No one can argue that we are not dealing with something important.

However, many things on the national agenda are important. What we must ask is: Is the concept right, is it good, is it timely? For whom is it right, for whom is it good, for whom is it timely? The answers to these questions depend on the context of the times and on the "whoms" we are considering. Let me discuss the context first.

It is often said that we live in an era of change; but when you think about that, change and pioneering have always been characteristics that epitomize this country. Our parents and grandparents came here to change their lives, and thousands upon thousands continue to do so today. Taking advantage of abundant, cheap natural resources—iron, coal, and fertile soil—as well as abundant, cheap labor, the individual inventiveness of the Edisons, Wrights, and Fords created whole new industries that came to underlie the nation's strength, prosperity, and quality of life.

In the second half of the twentieth century, we invested more deliberately in new technology as the output from a continuum of new scientific knowledge and new engineering approaches. The results included military and commercial jet aircraft, lasers, computers, and the enormous field of microelectronics. As a nation, we have strongly benefited from basic research, especially that carried out at our universities, and from the scientists and engineers trained there in a forward-looking research environment.

These lessons have not been lost on the other nations of the industrialized and industrializing world. They, too, have learned how to systematize technological innovation, and have narrowed dramatically the technological leadership gap. All these nations are investing an increasing fraction of their gross national products in research and development, with Japan showing the most dramatic acceleration, along with an increase in attention to basic research, the area in which the United States has predominated for many decades.

Unless we respond effectively to this challenge, we face certain loss of technological and economic leadership in the world, with consequences that are not measurable in dollars alone. In short, we must rededicate ourselves to change. The President's Commission on Industrial Competitiveness recognized this when it warned that "the United States is losing its ability to compete in world markets." "We are still the world's strongest economy," the

Commission conceded, but "the question we must answer is where we will be tomorrow, not just where we stand today."* And that is the subject of this volume: change and leadership. One of the perils of leadership—of being number one—is that the strategy for staying ahead requires far more vision and determination than do the tactics for catching up.

What, then, must be our strategy for keeping our leadership position? First, we must use the knowledge and talent we produce in the most creative ways we can. Arbitrarily confining knowledge within various individual fields greatly restricts intellectual interchange; by contrast, encouraging interdisciplinary cross-fertilization enhances this interchange and promotes creativity. It should be obvious, for instance, that if artificial intelligence (AI) engineers can draw only on the work of other AI engineers, the number of insights and innovations they gain for their own work will be limited. On the other hand, if they are able to draw easily on the work of physicists, mathematicians, chip designers, biologists, and psychologists, the range of ideas at their disposal will multiply severalfold. After all, thinking is only the orderly rearrangement of ideas, and if more and more diverse ideas are available for rearrangement, the thinking process is likely to be far more creative.

The second step in more effectively deploying our research and development (R&D) resources, once the ideas are generated, is to reduce the time between this acquisition of creative scientific knowledge and its commercial application. In the international market, the first to apply a new technology or process gains a tremendous competitive advantage, leaving others to play catch-up. By the time these others have caught up, the leader often will have upgraded the technology or replaced it with an entirely new technology.

The microelectronics and aerospace industries exemplify the importance of being on the leading edge of technology. But technological leadership alone does not guarantee success. Often our international competitors have outperformed us by utilizing American-created technology to make higher-quality products.

---

* *Global Competition: The New Reality.* 1985. Report of the President's Commission on Industrial Competitiveness. Washington, D.C.: U.S. Government Printing Office.

David Packard, one of America's foremost industrialists, once observed that there are some close parallels between success in industry and success in professional sports. Three main factors, he noted, determine success. One is the technical skills of the individuals; but these basic skills often are about evenly distributed among teams, as they often are among competing companies or nations. So the other two factors frequently make the difference in the outcome of competition. One is the individuals' zeal to win, and the other is how well they work together as a team. The implications for our R&D process is that we not only must have the capabilities for promoting cross-disciplinary interchange and a rapid transition of ideas to the marketplace but we also must have the competitive spirit and built-in cooperation that will enable us to actually bring these goals about, and to do so with high quality.

Thus, the key ingredients we must seek are creativity, competitiveness, teamwork, rapid reduction to practice, and emphasis on quality. Given this list, it is not hard to see why the ERC concept has struck a resonant chord in these times. The Centers promote the kind of cross-disciplinary teamwork that emerging technological problems demand by bringing into a single research structure individuals from a wide range of engineering and scientific fields, as well as by collecting under one roof researchers with sharply different approaches to problem solving. The ERCs hold the promise of quicker translation of ideas into applications because of the two-way exchange of information and ideas between basic researchers and industrial engineers working side by side. And these Centers encourage the winning, cooperative spirit—the vitality needed to flourish in a competitive environment—because they are established with a single guiding purpose: the pursuit of engineering excellence.

I should add that the ERC concept was not just a shot in the dark. The federal government has used the multidisciplinary approach to good effect in the past. Twenty-five years ago, the Defense Advanced Research Projects Agency created Interdisciplinary Materials Research Laboratories (IMRLs) on some campuses that brought together chemists, physicists, and engineers working cooperatively on broadly defined basic research problems that were critical to the national interest. Today we are reaping the benefits of those laboratories with the generation of whole new disciplines in composites, structural ceramics, and polymers, as well as the production of materials with improved thermal, electrical, mechanical, magnetic, and optical properties.

Similarly, about a quarter century ago the United States began to invest heavily in molecular biology and biomedical institutes. Again, multiple disciplines joined together—not only biochemists and microbiologists but also chemists, physicists, mathematicians, and engineers. And now we have a substantial understanding of the biological structure of antibody molecules and the process that enables the human genetic system to generate such a great diversity of antibodies. This understanding will allow us to advance our knowledge of other biological processes and to exploit that knowledge through new approaches to the prevention, diagnosis, and treatment of virtually every human health problem.

Industry itself has recognized the benefits of this cooperative, interdisciplinary approach to problem solving. On their own, companies have formed more than 40 research consortia to find solutions to common problems, ranging from television transmission to plastics recycling. They also understand the importance of university linkages. Twenty-seven firms have combined to fund a robotics institute at Carnegie-Mellon University that, in the words of one corporate president, has "spun out applications in two or three years instead of the normal five." And at Ford, we have recognized that if we are to remain competitive in the years and decades ahead, we must go beyond the strict disciplinary organization for conducting our research. Thus, we have been moving away from the discipline-focused approach and toward the problem-focused approach in our own research laboratories.

One of the great advantages of this interdisciplinary arrangement, especially as it is carried out at the ERCs, is that it allows us to concentrate on a single critical problem or a related set of problems. In other words, researchers come together from different fields not to contribute the whole range of their knowledge but to draw on that base of knowledge to select that which is most relevant to the problem at hand. This intensity of focus is the same principle that made the Manhattan Project in the 1940s and the space effort in the 1960s successful within very short periods of time. The main difference in concept is that, instead of a single type of application, now we are focusing on fields of research with potential applications across a broad spectrum of products and technological needs. Thus, while such subjects as systems research, composites manufacturing, combustion engineering, and net shape manufacturing do not carry with them the intrinsic glamor and immediacy of nuclear power or spaceflight, their ultimate impact on the economic welfare of our people may be many times greater.

There is, however, nothing sacred about this relative handful of particular subject areas chosen for the initial rounds of ERCs. Within an hour, I could probably come up with a list of 50, maybe 100, other areas of technology—and, indeed, of science—that would be just as useful as subjects for interdisciplinary research centers. That is just the point. The ERCs established so far are only the beginning of a whole new approach to competitiveness. They are not intended to be short-lived ventures with specific technological goals in a few areas that can be achieved by a given date, with the Centers then being disbanded. Rather, they are intended to be long-term arrangements that serve as models for similar undertakings in many other areas of technology and science. The ERCs, in short, are not meant so much to be new institutions per se as much as they are meant to be new *processes*—new ways of carrying out our missions of R&D and education in a vastly more effective manner.

That brings me to the core of my argument. As valuable as the ERCs will be in conducting forefront work in technology, that is not their main purpose. There is no way that government or industry can predict what technologies will be needed a decade from now—or even what areas of technology will be critical to our economic competitiveness. All that we can predict with assurance about the future is that technologies virtually unheard of now will be as prominent then as biotechnology, circuit miniaturization, and artificial intelligence are today; that these technologies will become indispensable to our ability to compete, and will do so even faster than current technologies have; and that these new technologies will be increasingly cross-disciplinary in nature.

In order to be able to create and adapt these technologies, what we will need most are people who can operate comfortably across disciplines rather than just in a single discipline, who can see the interconnections between basic research and eventual applications, and who are imbued with the winning spirit. This is the talent aspect of our competitiveness that I mentioned earlier, and the creation of this adaptable, flexible talent is the overriding purpose of the ERCs. Indeed, future technologies are just the realization of this talent. As the President's Commission on Industrial

Competitiveness emphasized, technology is not a "thing." Talent is not separable from hardware, because human know-how is the central ingredient of all technology that we produce. And the more flexible and adaptable that talent is, the better the resulting technology will be. Thus, the goal of the ERCs is to consciously expand that flexibility and adaptability. We are not so much looking for new kinds of robots, materials, or the like from the ERCs, although that would be nice to have. What we are looking for most are new kinds of people—researchers who can perform in top fashion in a rapidly changing, highly competitive, highly interdisciplinary world.

It is clear that the Engineering Research Centers address important national and industrial goals. But are they good for our universities? After all, the high quality of our educational institutions is, in no small measure, due to the ability of researchers to pursue ideas in an unfettered manner within a discipline-oriented structure. Will they become distracted by the emphasis on relevance and by industrial "interference," and will interdisciplinarity reduce the quality and depth of knowledge? Of course they would be, if these trends were carried to extremes. It would be simply disastrous if our universities were to be controlled by the whims of outside parties and if the disciplinary identity were to be lost. But I believe that the introduction of a reasonable degree of industrial perspective and experience will surely broaden the possibilities and enrich the environment of universities. Likewise, I speak from experience when I state that anything that increases communication and cooperation across departmental boundaries will broaden the faculty and improve the education of students.

I fully believe, then, that the ERC concept is an idea whose time has come. It is not a panacea; but the melding of fields of knowledge, with government, universities, and industry all working as a team toward common long-term goals in a people-oriented environment, is a powerful formula for success. The beginnings have been good. It is up to us all to continue to strengthen this leadership for change.

Part II

THE FIRST YEAR: LESSONS LEARNED

A New Experience: Lessons Learned by the National Science Foundation

NAM P. SUH

I am happy for this opportunity to make a few remarks about the Engineering Research Centers (ERCs) program. It is no secret that at the National Science Foundation (NSF) we are proud of the ERCs. We have high hopes for their future. We believe that they are breaking new ground in engineering, and that they are going to help in the long-term effort to improve our nation's international competitiveness.

SIX LESSONS

Even though the first ERC awards were made barely a year ago, NSF has already learned a number of important things about them and about the U.S. engineering community that are going to be critical factors in our efforts to build engineering and technological strength in America. Let me list just six of these findings.

First, our engineering schools have shown that they are anxious to do pioneering work in cross-disciplinary research, and that they have a wealth of ideas for pushing engineering forward through the Engineering Research Center structure.

All together in the first two competitions we have received 244 proposals for Engineering Research Centers from 114 engineering schools requesting a total of $3.5 billion in support. What makes those numbers even more significant is the fact that NSF had only

$10 million the first year and $21.7 million the second year with which to respond to that $3.5 billion in requested funds. A lot of thought and work went into the preparation of those proposals, and we are told that many schools benefited from the experience even though they did not receive NSF funding.

In some cases states have provided support, and in one or two cases other federal agencies may provide funding. We anticipate that more states will establish ERCs in their state universities, because they can expect to reap major benefits from the relatively small investments they will make.

Second, we have learned that there is tremendous interest in industry for this type of industry-university interaction. That interest is real, as evidenced by the fact that industrial firms are putting up money and other resources to become full-fledged partners in this venture. Here is a striking statistic: Even at this early stage, for every federal dollar put into the ERCs, industry has put up $1.24.

Third, universities are coming through with the strong backing necessary for the Centers' success. So far, this crucial university support is evident at all 11 institutions where Centers have been established. It is a little early to pass final judgment in this area, but we are encouraged by the experience so far.

Fourth, we are convinced that for the U.S. engineering infrastructure to be strong, we must have a proper balance between, on the one hand, cross-disciplinary and single investigator-initiated research and, on the other, research in traditional engineering sciences and emerging engineering fields. The cross-disciplinary research area is currently the weakest and requires strengthening—as the ERCs are intended to do. But at the same time we must make certain that support for the individual research project also remains strong.

Fifth, the ERC program is a positive step forward in strengthening the international competitiveness of the United States. However, it is only a start on what must ultimately be done to bring U.S. engineering to the level of excellence it should attain if we are to continue to be a world leader in technology. It will require a much larger investment in engineering research to create the technological options needed to make sound socioeconomic and political decisions that can enhance our international competitiveness. A realistic estimate of the amount needed to enable NSF's engineering program to make a difference is about $500 million annually.

Sixth, other nations are envious of our ability to move forward with a new research centers program like this one in such a short time. While we often joke about Washington's red tape, the fact is that both the executive and legislative branches can, and often do, move quickly to establish a priority program. The "gestation period" for the ERCs was only about 19 months from idea to funding. Thanks to some excellent planning in implementing the program, the first ERC proposals were due in to NSF on October 1, 1985 (the beginning of fiscal year 1985), and awards were announced just seven months later. I believe the people at NSF have done a fine job in bringing this program along.

The agility of our governmental system and the willingness of Congress and the Office of Management and Budget to support a promising new program, even under severely constrained budgetary circumstances, is a credit to all who are involved in the process. It is one of our nation's strengths. It gives us an edge over many of our counterparts overseas who must deal with much more cumbersome and bureaucratic systems.

THE ROLE OF THE ERCS

Innovation and Education

At NSF we expect that the cross-disciplinary research conducted at the ERCs will, over the long term, trigger the development of new technologies by industry. We also expect that the unique educational experience provided both graduate and undergraduate students at these Centers will better prepare them to practice engineering after graduation.

Consequently, we see the Centers helping industry with the task of meeting foreign competition through both research and education. The problems of international competitiveness are complex and pervasive. I think it is obvious that these problems go far beyond the quality and nature of research. Nevertheless, it is clear that the United States must continue to do what it has done best in the past to enhance its international competitiveness: Studies show that, in the past, the United States has benefited more from technological innovation than from any other competitive factor. Thus, it is clear that we must continue to generate creative engineering graduates as well as creative research.

In this general context, a brief story might be appropriate. A French, an American, and a Japanese engineer had all been tried and convicted of a serious crime. They were sentenced to hang. When they were taken to the gallows, the executioner asked if they had any last requests. The Frenchman asked to be hung last, and the executioner agreed. The Japanese engineer asked if he could be permitted to read aloud a short article on Japanese management that he had in his pocket. The executioner said he could have one minute to do so, but that, first, he wanted to let the American express his wish. The American engineer looked up and said, "Please, hang me now. I couldn't stand to listen to another talk on Japanese management." This story helps to make the point that we must seek our own solutions for enhancing our international competitiveness by making use of our own strengths and cultural heritage rather than trying to emulate others, whose background and constraints are very different from ours.

Cross-Disciplinary Research

The ERC program was created in part to overcome an existing weakness of our engineering schools—namely, their inability to conduct cross-disciplinary research. It is not that cross-disciplinary research is a new idea or concept. Actually, it is as old as engineering itself in the United States. We started out with military and civil engineering in the building of roads, forts, arsenals, waterworks, and so on. As time passed, new disciplines such as mechanical, electrical, and chemical engineering were established as an outgrowth of cross-disciplinary research efforts among existing engineering and science disciplines.

Over the past 40 years our engineering schools have become increasingly specialized in an effort to strengthen the engineering science base—an appropriate emphasis during that period. Consequently, the existing university culture tends to operate within the boundaries of numerous well-established disciplines. That presents a difficult environment for cross-disciplinary research. We needed a new mechanism to permit that type of research to flourish, and the ERCs are proving to be a very popular way of making it happen, judging from the large number of universities that want to have one.

The road ahead for the ERCs will not be an easy one. Each of the Centers must mature in a system that has, for many years, recognized and rewarded individual instead of team effort. The Centers may also experience difficulty in maintaining the team spirit needed to foster cross-disciplinary research because, as John McTague pointed out (see previous paper, this volume), in most cases they do not have a specific engineering product, such as a Space Shuttle, to produce. Their focus is at once more basic and more broad than that, so team goals are necessarily not as clear-cut.

Planning for the Future

It is also important that each Center develop a strategic plan. These plans and the goals of the Centers must be in harmony with the long-range goals of the university wherein each Center resides. They must have a contingency plan that will carry them beyond the five-year period of NSF funding. I want to stress that, for its part, NSF plans to continue funding for as long as a Center is doing a good job (and for as long as NSF has the funds available). The point is, if the universities believe that the ERCs are performing a very important function, they are likely to continue hosting the Centers even if NSF is not able to continue providing support for them. But each Center will have to plan for the *possibility* that it will need to be self-supporting. It is important that each Center get students and professors alike to understand the strategic goals of the Center and what their individual roles are in achieving those goals.

Gaining NSF support is, of course, a big hurdle in establishing an ERC; but an even more difficult task may prove to be implementing and establishing ERC concepts—what we might call an "operational philosophy"—that are worthy of an outstanding university.

Obviously, for the ERCs to achieve their goals they must work closely with industrial firms. We are gratified to see the spontaneous support and response of U.S. industry to the ERC initiative. The Centers, for their part, have done a good job of involving industry in their endeavor in an appropriate and mutually beneficial way.

Leadership

I would like to compliment each of the ERC directors. One of the most important criteria in selecting a proposal for support was the leadership—both intellectual and managerial—of the proposed Center director. We are very satisfied with the results. It has been a privilege for me to get to know each of the directors. At the same time, we recognize that the ERCs themselves must be built into entities that are sufficiently strong to survive the leadership changes that will come, as surely they do in all organizations.

THE WILL TO WIN

Thus, it is a combination of leadership and institutional strengths, plus first-rate research, that will carry the ERCs forward. The first 11 Centers have an excellent chance to score high in all three categories and to fully meet the stated goals of the ERC program.

A point I want to stress is that the United States is in very serious competition for technological leadership. It is a long-distance race. We will not know the outcome for some years. To win will require a tremendous investment in research—particularly in engineering—and a coming together of our universities, industries, and federal agencies and government research laboratories.It may be the greatest challenge we have faced since World War II.

My 20 months in Washington as assistant director for engineering at NSF have been quite revealing. I have met with engineers and representatives of many countries who are involved in engineering and technology. There can be no question that our international competitors are determined to be first in engineering. They are devoting tremendous resources to that effort, and they intend to win.

We can meet that challenge and continue to be the world leader in technology if we make the commitment now, all of us, to the task at hand. That means making our research efforts in the engineering disciplines, in the Engineering Research Centers, and in federal and industrial laboratories second to none. We must dedicate ourselves to this task so that Americans can continue to enjoy a high standard of living and expanding opportunities. It will require that we be strategic in our planning and creative in our technical work. The ERCs should prove to be of tremendous help in this effort. Indeed, they should become models of the will to win in technology.

DISCUSSION

Dr. Suh was asked to give his view of the future of the ERC program. He responded that his main concern was to keep the overall program growing. The 1987 budget request is for $35 million for 4–5 more Centers, expanding to a total of 25 Centers by 1989. He emphasized that NSF has other thrusts intended to strengthen the nation's engineering infrastructure, including support for emerging technologies (e.g., biotechnology, lightwave technology, computation engineering), for completely new fields such as neuroengineering, and for engineering systems (e.g., ocean, transportation, power, and water engineering systems). Other questions dealt with the criteria used in selecting and evaluating ERCs. Dr. Suh explained that NSF had decided not to establish priorities for ERC topics during the early phases of the program; as the number of Centers approaches 25, however, the range of Centers will be assessed to see if priorities then need to be set. Regarding evaluation criteria, he said that the National Research Council is addressing the question of how best to evaluate the ERCs; NSF has also established management teams to track technical progress. However, he expressed his belief that the success or failure of such a Center is usually obvious without detailed measurement, and that the monitoring/evaluation should not be allowed to impede the Center's progress.

Systems Research Center

JOHN S. BARAS

INTRODUCTION

The Systems Research Center (SRC) at the University of Maryland, College Park, and Harvard University, Cambridge, Mass., is a new forum for fundamental research and education in systems engineering.

Established by a National Science Foundation (NSF) grant in 1985, the SRC is developing advances in design methods and software systems that innovatively address the challenges of productivity and competitiveness facing American industry. At the same time, the Center is training a new generation of systems engineers in an environment that is designed to both expand intellectual frontiers and achieve important research objectives.

SRC Goals and Themes

The impetus behind the activities of SRC is a close and mutually supportive collaboration with industry and government. The Center's programs are designed for two purposes: (1) to make the best possible use of the expertise and interests of an interdisciplinary team of faculty members and available private and government research personnel and facilities, and (2) to meet objectives consistent with the competitive needs of business and industry.

The Center's research theme is to promote basic study in the applications and implications of advanced computer technology—very large scale integration (VLSI), computer-aided engineering (CAE), and artificial intelligence (AI)—in the engineering design of high-performance, complex automatic control, and communication systems. Its research activities are built around five interrelated focus application areas: chemical process control, expert systems and parallel architectures, manufacturing systems, communications systems and signal processing, and intelligent servomechanisms.

Traditional industries as well as high-technology industries depend in a critical way on automation and information processing systems. As the complexity and demand for these systems has increased dramatically in the past decade, it has become obvious that the modeling and design methodologies of the past are no longer adequate. More emphasis is needed on the modeling and empirical/experimental components of systems science and engineering. In addition, sophisticated system-level design tools are needed to integrate the analytical and computational techniques of control and communication engineering with advances in computer hardware and software. These system-level design tools will increase the productivity and efficiency of engineers and will facilitate teamwork. The Center's programs represent a premier example of the use of advanced computer technology as an "amplifier" of human engineering skills and ingenuity.

The Center's educational goals are to support and enhance education programs and to serve as a source of new courses and material. In the process, the Center is seeking to change the traditional focus of engineering education by placing a new emphasis on both education and training. The Center's broad, interdisciplinary programs, offered in cooperation with Harvard University's Division of Applied Sciences, cut across the boundaries of many engineering and computer science disciplines, and they are designed for interactive participation by America's foremost corporations. The ultimate goals are to gain new knowledge; to train the engineers who can apply this knowledge to a diverse set of complex, real-world problems; and to speed the transfer of research results to the industrial community.

To enhance the interaction among the academic, industrial, and government research communities, an innovative and broad industrial collaboration program has been established. It includes joint research projects, industrial visitors to the university, faculty and student visitors to industry, joint use of laboratories, fellowship programs with industry, intensive short courses and workshops, colloquia, seminars, a software library, and a unique software research "club."

In this paper I will describe the progress that has been achieved to date in the research, educational, and industrial collaboration programs of the Systems Research Center. I will also provide a brief preview of our plans for the second year.

Initial Goals

Let me first briefly recall the goals we set for SRC upon its creation:

• Pursue integrated design of complex automation and information processing systems. Create a computer-aided design (CAD) environment where complete integration can be achieved, from conceptual development to technology selection, hardware implementation, testing, and validation.

• Emphasize modeling, empirical, and experimental issues. It is exactly this component of systems science and engineering that we felt had been neglected over the past 15 years or so. In particular, we wished to emphasize modeling of the new hardware systems used to implement the control or information processing algorithms.

• Develop design theories and tools that incorporate advances in computer technology (hardware and software). This goal was based on the realization that control and communication system design methodologies were not in synchrony with the currently available or planned implementation media.

• Provide real engineering tests for design. We wanted to increase the awareness of both faculty and students about the difficulties inherent in executing and validating a design.

• Provide engineers with system-level design tools that are able to increase design productivity, quality, and efficiency. These tools should include the heuristic/empirical component of the design process, as well as the analytical/numerical sophistication of the new theories.

OVERVIEW OF ACCOMPLISHMENTS

It has been a very exciting year at SRC. Building the organization, infrastructure, and mechanisms needed to support the various programs has been a demanding but intellectually rewarding endeavor for all involved. Let me give an overview of our accomplishments during this beginning period. We initiated a broad, innovative, interdisciplinary research program that I will describe in greater detail in a later section. We undertook several educational innovations and developed advanced design teaching laboratories. We established a broad industrial collaboration program. We began the development of several advanced research laboratories. And we completed the organizational and administrative structure of the Center.

We paid particular attention to developing appropriate policies for faculty and student participation. We firmly believe that early recognition of the significance of these policies is a critical component for the long-range success of such centers. SRC involves 2 universities, 2 colleges, 6 departments, 36 faculty, 50 graduate students, and 30 undergraduate students. It is apparent that without a strong "joint venture" spirit supported by such policies, long-range success may not be possible. The Administrative Council (which includes the chairpersons of the major participating departments, the deans, representative executive officers from industry, and the SRC director) proved to be a very efficient vehicle for formulating and implementing such policies.

We have already made great strides in diversifying the financial support for the Center. In addition to funds from NSF, funds are being provided by other federal and state agencies, the universities, and industrial sponsors. We are grateful to industry for the spontaneous response, both in funds and equipment gifts, that they displayed during our first year of operation. In the first year we received funding of about $2 million from NSF, $0.4 million in funds and more than of $2 million in equipment gifts from industry, and $0.3 million from the state of Maryland and the two universities. In addition, the universities provided space and faculty positions. Eight new faculty have been added at Maryland and one at Harvard as a result of the creation of SRC.

Let me close this section by summarizing the response as I observed it during the first year. From academic faculty the response has been enthusiastic; many more people want to participate in the SRC program than we can currently accommodate. From industry I can characterize the response as extremely supportive and as a "long-awaited dialogue." We have been very encouraged by the convergence of ideas and plans between industrial researchers and our academic faculty on the subject matter of our research. Finally, the response from students has been overwhelming. It has created an unprecedented excitement on campus, so that we have had five times as many applicants as we could accommodate. In particular, the possibilities for real industrial interaction proved to be extremely attractive to students.

THE RESEARCH PROGRAM

As described elsewhere in further detail (see References), the research program of the Systems Research Center has been evolving around five focus application areas. During the first year, serious efforts were undertaken in all areas to introduce computer-aided engineering, along with experimental and empirical design issues, and to cross the traditional boundaries between the multitude of disciplines represented at SRC. In addition, we put particular emphasis on the involvement of undergraduate students in design projects as early as possible in their careers. As emphasized elsewhere (Baras, 1986), the subject of fundamental studies carried out at SRC is in a sense systems science and engineering itself, and not its particular application or manifestation in a narrow application area. This in itself justifies the emphasis that we have placed on system-level design tools for automation and information processing systems.

Our findings throughout the year not only reinforced some of our beliefs and expectations in the value of our approach to systems engineering but also rewarded us with the discovery of some unsuspected connections between totally unrelated engineering problems. Several key ideas and concepts have already emerged: (1) a pervasive utility of optimization-based design in a great variety of engineering systems; (2) the value of AI in the development of systems that can reason and that can aid in the design process; (3) the superior efficiency and ability of symbolic algebra as an engineer's aid in complex calculations and modeling; (4) the critical importance of representation and manipulation of engineering data bases; (5) the mandatory utilization of AI techniques to handle heuristics in the design process and to enhance and facilitate teamwork; (6) the mandatory utilization of interactive graphics as the interface mechanism between the systems engineer and the computer; and (7) the critical importance of understanding VLSI systems, their architectures, and their limitations.

It is impossible in the limited space and time available to describe the multitude of exciting projects currently undertaken by SRC faculty and students. Instead, I will present an overview of the research program and will highlight certain sample projects to illustrate the nature of our work and our findings. The selection of projects discussed reflects, to a certain degree, my finite memory and capacity to represent the details of many excellent projects that are under way and reflects my perception of projects wherein intellectual integration across disciplines has occurred most extensively.

First, the focus areas and the thrusts within each area are as follows:

1. *Intelligent Servomechanisms.* Major thrusts are the design of robust control systems with many sensors and many feedback loops and, in particular, advanced robotic manipulators and flight controllers for advanced aircraft and spacecraft.
2. *Chemical Process Systems.* Major thrusts are modeling and control of industrial processes and the integration of reliability and safety in the computer-aided design process.
3. *Manufacturing Systems.* Major thrusts are the integration of CAD with manufacturing resources planning (MRP), scheduling and resource allocation problems in flexible manufacturing systems, and applications of AI in manufacturing.
4. *Communication and Signal Processing Systems.* Major thrusts are the modeling, design, and control of computer and communication networks, image processing, and speech processing and recognition.
5. *Expert Systems and Parallel Architectures.* Major thrusts are VLSI systems design and architectures for control and communication systems, expert systems for control and signal processing, and reliability integration in computer-aided design.

From the beginning we have emphasized the need to design and develop our specialized research laboratories so as to create a sophisticated environment for integrated design. The constituent laboratories are a key concept in our development of SRC. These laboratories form the natural home for interdisciplinary groups of faculty and student researchers. In a sense the entire research and educational program of SRC evolves around these constituent laboratories. I would like to describe briefly the components of this environment. We have developed the notion of a system engineer's workstation, which is really a design super-workstation combining an AI machine with a graphics engine and a multiprocessor "number cruncher." This super-workstation is part of a network of other workstations and computers (both similar and different) so that the engineer can have the capability of running concurrently several modules of his or her design software system on different machines. The AI workstation provides the direct interface with the user for (often symbolic) problem description and modeling. The multiprocessor number cruncher provides the necessary computing power for almost real-time execution. Finally, the graphics engine provides real-time graphics for simulation, testing, validation, and feedback to the designer.

We have also emphasized the integration of symbolic and numerical computation. We are convinced that symbolic languages such as LISP, PROLOG, and MACSYMA offer a superior medium for definition, conceptualization, and implementation of design problems. They are also superior for modeling engineering systems. An additional advantage offered by these languages is their superiority as universal communication tools between engineers and scientists from diverse disciplines and backgrounds.

We have introduced and implemented sophisticated simulation tools. These include analytical, software, and hardware tools. For example, we plan to use critical sampling theory for fast Monte Carlo simulation in computer/communication networks and manufacturing systems. The mathematics justifying such techniques, which reduce simulation times by several orders of magnitude, are quite sophisticated. We also plan to use LISP-based and object-oriented programming for high-level simulation of chemical plants, flexible manufacturing plants, and communication networks. All laboratories will be linked to real-data experiments for testing and validation of proposed designs. We plan to rely heavily on AI and expert systems, to handle the routine and heuristic part of the design automation, and on graphics for the man-machine interface. Examples of the environment we are creating will be given below in the description of selected research projects.

Intelligent Servomechanisms

In the area of intelligent servomechanisms we had the following projects: bifurcation control and multiparameter singular perturbation (with applications to flight control) (Profs. Abed, Krishnaprasad, and Tits); complex analytical methods for design of controllers and signal processing schemes (Profs. Berenstein and Baras); hand-eye machine (Profs. Brockett, Maragos, and Wohn); nonlinear control and robotic manipulators (Profs. Krishnaprasad, Berenstein, Tits, and Abed); and optimization-based CAD (Profs. Tits, Krishnaprasad, Baras, and Levine).

I would like to provide some details about the project on nonlinear control and robotic manipulators, which is under the direction of Prof. Krishnaprasad. Research in this project ranges from specialized hardware design and construction to very sophisticated theories of nonlinear dynamics of multibody systems. Progress has been achieved in several directions. Professor Krishnaprasad, in collaborative work with Prof. J. E. Marsden (University of California, Berkeley) and Prof. Juan Simo (Stanford University), worked out the Hamiltonian structure of systems of rigid bodies with flexible attachments that obey finite strain elastic models and that are geometrically exact. These results should have a significant impact on the control theory of multibody spacecraft and on the modeling and control of flexible robotic manipulators. The researchers have also been able to establish the Poisson structures underlying a wide variety of problems in interconnected rigid body systems and have used these to obtain stability criteria for various equilibria. Certain examples have been simulated and displayed graphically on our IRIS workstation to reveal for the first time the beautiful topological structures of the phase portraits. Our results here should prove useful in the study of control problems for articulated spacecraft and robotic manipulators operating on space platforms (e.g., the Space Station Mobile Remote Manipulator System, or MRMS).

A group of 10 students was involved in a design project under the sponsorship of National Aeronautics and Space Administration (NASA) Headquarters, NASA Goddard Space Flight Center, and the Systems Research Center. The project is under the supervision of Prof. P. S. Krishnaprasad and is 1 of 18 projects under way in universities across the nation as part of the NASA-funded pilot program in advanced space systems design. A primary goal of this NASA program is to encourage and strengthen design-related activities in university curricula at the undergraduate and graduate levels. The goal of the project at the University of Maryland is to design a Mobile Remote Manipulator System for the Space Station. Students participating in this project receive academic credit.

Throughout the year, strong collaboration continued with Harvard in the area of robotic manipulator design. In the project directed by Prof. Brockett, a 9-degree-of-freedom hand is now operating under closed loop position control and 3-degree-of-freedom force control as well. It is currently being used in the Automatix AID600 robot, and software is being written which will make the hand programming easier. Victor Eng's thesis work involves the incorporation of modes into a hand programming language. It is our belief that the control of multi-degree-of-freedom systems will be greatly facilitated by the identification of coordination patterns, or modes, which, while not completely general, allow one to execute frequently occurring motions in a simple way. The situation is analogous to the use of glyphs in graphics—in fact, one can think of modes as "motion glyphs." A closely related idea involves the coordination of sensory information. Here, sensory glyphs are identified with those combinations of sensory output data which occur frequently so as to make it possible to easily set up feedback control loops for regulators. This feature is also being incorporated into the hand control programming environment under development.

A distributed tactile sensor is being developed at the Naval Research Laboratory in support of the distributed sensor work at SRC (Prof. Shamma). This is an all silicon design based on a clever application of piezoresistive and piezoelectric phenomena in conjunction with an amplifier/multiplexer chip for local processing so as to recover estimates of the three components of the applied force field. The sensor can also detect slipping between the manipulator gripper surface and the object. Strips of the material can be attached to the fingers of a manipulator hand, and signal processing is performed by neural-type processor chips.

Chemical Process Systems

In the area of chemical process systems we had the following projects: automation of dynamic process simulation (Prof.

Cadman); modeling, simulation, and control of chemical reactors (Prof. Choi); application of expert systems to distillation column control (Prof. McAvoy); and knowledge-based expert systems for chemical plant operations (Prof. Modarres).

I would like to give some details on the project directed by Prof. Choi on the development of advanced control strategies for a class of industrially important polymerization processes. The research in this project ranges from developing detailed mathematical models for free radical and condensation polymerization reactors (for various reactor configurations: continuous, batch, and semibatch), to building research pilot plants for experimentation and design testing, to implementing advanced closed-loop control based on the sophisticated theories of stochastic control and nonlinear estimation. Many industrial polymerization processes are characterized by high release of reaction heat, complex polymerization kinetics, nonidealities in micromixing and macromixing, nonlinear reactor dynamics, and a lack of adequate on-line sensors to measure the progress of reaction and important polymer properties.

High productivity, precisely controlled polymer properties, improved reactor safety, and flexibility in reactor operation are the major objectives in highly profitable polymerization processes. Many industrial polymerization processes are rather custom designed, and it is difficult for reactor operators to adjust reaction conditions effectively to meet new product specifications.

The research under way at SRC is aiming at the development of efficient software tools for process analysis and control, based on enhanced understanding of intrinsic characteristics of polymerization systems. A combination of sophisticated theoretical and experimental work has been undertaken. Current interest is focused on the following polymerization systems: high-conversion suspension polymerization of methyl methacrylate with high monomer/water charge ratios, solution copolymerization of styrene and acrylonitrile, precipitation and solution polymerization of acrylamide to produce water soluble polymers, and polymerization of high-impact polystyrene. The mathematical models of these processes will be validated by real-time measurement systems and by the sophisticated simulation tools being developed for the research pilot plant. Fully digital controllers will be designed that utilize real-time measurement devices such as on-line densitometers, on-line viscometers, and on-line gel permeation chromatographs. A particularly innovative feature of the project is the use of advanced real-time estimation algorithms and sophisticated control system design techniques.

Other exciting developments in this area include the development of expert systems for chemical reactor safety analysis and safety incorporation in design (Prof. Modarres) and the development of AI/optimization-based, multi-time-scale scheduling and planning tools for chemical plant operation and design (Profs. McAvoy, Asbjornsen, Tits, and Baras).

Manufacturing Systems

In the area of manufacturing systems we had the following projects: flexible manufacturing cell (Profs. Anand, Kirk, and Nau); computer-integrated manufacturing (Profs. Harhalakis and Mark); discrete-event dynamical systems and manufacturing automation (Profs. Ho, Makowski, and Baras); manufacturing of thermoplastics (Profs. Azarm, Choi, Hammar, Mechlenburg, Pandelidis, Pecht, and Smith), and printed wiring board design and manufacturing (Profs. Pecht and Palmer).

I would like to provide brief descriptions of some well-integrated projects in this area. In a project directed by Prof. Nau, new methodologies are developed for knowledge representation and reasoning for process planning. The interdisciplinary team also includes Profs. Anand, Kirk, and Harhalakis. This research is based on a new frame-based approach to knowledge representation called "hierarchical knowledge clustering." In most frame-based reasoning systems, the data manipulated by the system are represented by using frames, but the problem-solving knowledge used to manipulate these data is represented as production rules. However, this is not always the best approach. Production rules are not always a natural way to represent knowledge—and in addition, rule-based systems containing large knowledge bases may require excessive computation to determine which rules are applicable. Hierarchical knowledge clustering provides ways to address these problems, yielding a more natural way to represent knowledge as well as improved computational efficiency.

A prototype system using hierarchical knowledge clustering was implemented in PROLOG, in a system called SIPP. An improved version is being implemented in LISP, in a system called SIPS (Semi-Intelligent Process Selector). SIPS is being adapted for use in process planning in the Automated Manufacturing Research Facility (AMRF) project at the U.S. National Bureau of Standards (NBS). Further research in this area will involve extending the approach used in SIPS to develop a practical AI-based process planning tool. Ideally, this tool will be capable of producing process plans for complex objects completely from scratch, using only the specification of the part to be produced and knowledge about the intrinsic capabilities of each manufacturing operation. The planned research requires the development of ways to integrate solid modeling techniques with AI reasoning and problem-solving techniques (e.g., ways to extract meaningful features from solid models), as well as the development of more sophisticated ways to reason about the properties of three-dimensional objects; work is also under way on a new approach to solid modeling.

The advent of computers in almost every manufacturing corporation, together with the plethora of relevant software packages aiming at increased efficiency and profitability, has produced an uncontrollable situation. Attainable benefits evaporate due to the unprecedented multiplication of input, maintenance, and output and the amount of money and manpower required to implement and coordinate all these systems.

In recognition of this problem we have initiated an integration project headed by Profs. Harhalakis and Mark that will eventually lead to minimization of data transfer and of the burden of running such a variety of "data vehicles" and data processors. A core system, Manufacturing Resources Planning (MRP II), is suggested to host computer-aided design as a first step toward integration. MRP II is by definition addressing all facets of industrial business, from marketing planning through engineering to manufacture, final inspection, and shipment. CAD is meant to assist the front end of the product life cycle and to focus on engineering, design, and drafting related activities.

The integration will be founded on a data base level. Sample features of the proposed integration include the following:

- automatic part master record generation and single-level product structures on completion of a new CAD drawing,

- engineering change control via checks performed at inventory and order levels and through status messages transmitted to MRP II and CAD screens, and
- the ability to retrieve and query pictorial and textual information on parts and assemblies at every level of the organization.

It is estimated that a large number of companies already using or planning to use MRP II and CAD will benefit substantially from such an integrated set, which ensures a smooth and effective flow of information. Future plans include the establishment of more links between MRP II and computer-aided manufacture (CAM), computer-aided testing (CAT), and others—all of them aiming at building ultimately a single computer-integrated production (CIP) system.

As an extension of this project, and in recognition of the critical significance of engineering data bases in engineering design, we have initiated a new major project on engineering information systems under the direction of Prof. Roussopoulos. As a result of SRC projects, the data base group of the Computer Science Department was increased by two new faculty members. All computer-aided design/engineering activities will be supported by Engineering Information Systems (EIS) which are based on the following technologies: data base management, AI, and distributed processing systems. The environment of an EIS is naturally distributed. Therefore, all the concurrency and consistency control of distributed data bases is present. Furthermore, an EIS has additional distribution requirements that are distributed by the presence of tools interacting with it. The basic research undertaken here is for the development of an object-oriented data base management system to support EIS. More specifically: (a) an object-oriented data model for defining engineering objects is being developed, as are (b) the data base protocols needed for concurrent access and update of multiple-version objects and (c) access methods and update protocols of distributed EIS architectures.

Communication and Signal Processing Systems

In the area of communication and signal processing systems we had the following projects: performance evaluation and design of queuing networks (Profs. Makowski, Baras, Ephremides, and Tripathi), multiuser channels with uncertain statistics (Prof. Narayan), link performance in the presence of co-user interference

(Profs. Geraniotis, Ephremides, and Narayan), mobile radio networks (Profs. Ephremides and Geraniotis), design and analysis of data compression schemes for image and speech signals (Profs. Farvardin and Shamma), speech analysis and recognition (Profs. Shamma, Peckerar, and Farvardin), mathematical methods for spectrum estimation (Prof. Benedetto).

I would like to describe now briefly some well-integrated projects. We have initiated the development of a computer and communication network laboratory, where sophisticated simulation, performance evaluation, optimization, and design tools are being developed. In a joint project with AT&T Bell Laboratories Prof. Makowski is analyzing and enhancing the Performance Analysis Workstation (PAW) performance evaluation system. The system employs direct graphical input for queuing systems representing computer systems, communication networks, and manufacturing production lines. It has the capability of computing various statistics of the network. In a broader effort Profs. Baras, Ephremides, Geraniotis, and Makowski have initiated the development of advanced simulation and optimal design tools. The key idea is to develop distributed LISP-based, object-oriented programming tools for simulation and control of complex, variable networks. We also plan to link these systems with more traditional discrete event simulators and optimization-based design of adaptive, distributed network control algorithms and protocols. This effort is a perfect example of the laboratory/design environment that we are creating at the SRC. In a related effort Profs. Davisson, Ephremides, Farvardin, and Geraniotis are developing a sophisticated hybrid (software and hardware combination) channel simulator.

Professor Farvardin has been studying intensively combined source channel coding and optimum entropy-constrained block transform coding. The first topic addresses the design and analysis of data compression schemes when the output of the data compressor is to be transmitted over a noisy channel. Here, the channel is modeled as a binary symmetric channel. An algorithm for optimal design of the quantizer and the optimal code word assignment is devised.

The second topic includes the analysis of a block transform coding system in which the average squared error is minimized subject to an overall constraint on the output entropy of the encoder. An algorithm for the optimal design of the quantizers, including the optimal entropy assignment, is developed. Research is under way to replace entropy-constrained quantization by permutation coding which has a block structure and thus does not suffer from problems associated with variable-length coding. Future work will address VLSI implementation of these schemes.

Professor Shamma, in collaboration with scientists and engineers from the National Institutes of Health (NIH) and the Naval Research Laboratory (NRL) has been investigating issues related to the front-end processing and recognition of speech phonemes using models of the mammalian auditory nervous system. The work involves three phases. (a) The analysis stage: the development of biophysical models and digital implementations of the auditory periphery to generate new, richer, and more robust representations of speech. (b) The recognition stage: neural network models mimicking the parallel distributed architecture of the central nervous system are used to perform various phoneme classifications. (c) The experimental stage: the integrated circuit fabrication of recording microelectrode arrays with CMOS (complementary metal oxide semiconductor) amplifiers and multiplexers to be used for further acquisition of experimental data necessary for the above modeling efforts.

Expert Systems and Parallel Architectures

In the area of expert systems and parallel architectures we had the following projects: integrated CAD of real-time non-Gaussian signal processors (Prof. Baras); an expert system for stochastic nonlinear control and filtering (Prof. Blankenship); VLSI systems (Profs. Ja'Ja' and Nakajima).

Professor Blankenship, in collaboration with J. P. Quadrat from INRIA (Institut National de Recherche en Informatique et Automatique, Le Chesny, France), has been developing an expert system based on symbolic manipulation programs for the analysis of stochastic control and nonlinear filtering problems. This software system brings to the practicing engineer, in directly usable form, such sophisticated techniques as Bellman's dynamic programming. Professor Nakajima has been investigating several problems in VLSI layout and silicon compilation. The ultimate goal is to develop a hierarchical layout design system for VLSI circuits. Recently, the development of efficient algorithms for the topological aspect of the circuit layout problem on a single layer was completed. Research on the multilayer layout problem has been initiated. In particular, we have developed an efficient channel-routing algorithm for three layers. Experimental results show that this algorithm produces, in most cases, a channel-routing pattern that requires a smaller number of horizontal tracks than previous algorithms. In the area of via minimization, a polynomial time algorithm has been developed for testing whether all nets of two or three terminals can be connected without using any via. Additional work is focusing on the development of a silicon compiler.

Professor Ja'Ja' has been investigating problems related to the complexity, architecture, design, and fabrication of VLSI chips with applications to signal processing problems. The automated generation of optimized circuit layouts from a high-level description is currently considered to be one of the most challenging problems in VLSI research. The ultimate goal is to relieve the user from all low-level details and to allow him or her to describe the design in a very high level language. The resulting layouts should be regular, compact, fast, and reliable. Recent research efforts have concentrated on a few less ambitious, general methods such as gate arrays, standard cells, and fixed floor plans. While these tools have been used successfully in the past few years, they all suffer from the fact that intermediate manual intervention is required in different phases of the design process and that they will generate highly nonoptimal designs even for some simple and natural tasks. We have been studying several fundamental problems that must be resolved before such optimized tools can exist. These problems include mapping logical functions into optimal layouts, placement and routing for special structured environments, and mapping structures represented by graphs into optimized layouts. Significant progress has been made for all of these problems.

A new approach for laying out logical functions has been developed using partially symmetric functions. A new software system called SYMBL (SYMmetric Boolean Layout) has been written to implement our approach. SYMBL is based on a strategy that first partitions the set of input variables into equivalence classes such that the given functions are symmetric with respect to each equivalence class. It turns out that this step can be implemented quite efficiently. The second main step is to determine a near-optimal "cover"—i.e., a set of appropriate subfunctions whose logical sum produces the function. We use a decomposition tree whose leaves are symmetric functions of the partitioned variables, and the partitions are combined as we go up the tree. Finally, the last phase consists of placement and routing routines that optimize the layout structure. The user can introduce his or her design in a high-level language which is then converted into a truth table. The truth table is handled by SYMBL, which produces the final layout without any intervention from the user.

We are also exploring the possibility of mapping functions into a general array type called Weinberger arrays. Two basic problems must be tackled in this approach. The first consists of manipulating the given functions into an optimized form. The second must place and route the Weinberger cells corresponding to the logical form obtained. This second problem can be formulated as a purely graph theoretic problem for which combinatorial tools are very useful. We have developed a set of good heuristic algorithms that work well for almost all cases. Our next step will be to implement these tools and to try them on real-world cases.

Several architectures have been proposed in the literature for handling basic signal processing computations. These architectures are highly regular and allow a good degree of concurrent processing. However, most of the implementations have considered the standard algorithms and have mapped them into these architectures. We have introduced fully pipelined structures that are based on a novel strategy consisting of decomposing a computation into a set of subcomputations that can be executed in parallel. A problem of size n will be roughly decomposed into $\sqrt{n}$ subproblems, each of size roughly $\sqrt{n}$, such that all these subproblems can be solved in parallel on fully pipelined, bit-serial systolic architectures. The class of problems for which such decompositions exist include filtering, convolution, and computing the discrete Fourier transform (DFT). We have shown that these structures can be implemented quite efficiently with compact hardware. As a matter of fact, we have designed a 25-MHz chip for computing the 240-point DFT that can handle up to 30,000 such computations per second.

Professors Baras and Ja'Ja', in a joint project with engineers from Sperry Corporation, are studying VLSI architectures for linear and nonlinear signal processing. Professor Baras has been developing the IDELPHI expert system for integrated design of VLSI chips for nonlinear, real-time signal processing. This software system has several modules: signal model development and validation, computation of sufficient statistics, architecture selection, and chip design. It will be intelligent enough, when fully developed, to understand the level of user expertise. It brings to the practicing engineer a sophisticated array of techniques and methodologies from stochastic systems, communication engineering, numerical mathematics, and VLSI complexity and architectures in a directly usable form. Several open problems in real-time sequential estimation and detection have been resolved by an innovative combination of sophisticated numerical techniques and VLSI architectures. Professor Baras and students LaVigna and Simmons are currently completing the design of a special purpose VLSI chip, the Zakai I chip, which provides a real-time solution to the celebrated nonlinear filtering problem. A printed circuit board prototype will be finished soon, and then the fabrication of the large (about 140,000 transistors) 22-MIPS chip will be undertaken. Our research here has revealed a major weakness of currently used signal models for communication and control: they are not properly structured for real-time processing. Planned research includes the investigation of massively parallel architectures (like connection machines), neural net-type architectures, and applications in adaptive array processing and speech processing for reduced bit-rate transmission.

The Value of the Approach

I would like to close this section with a few remarks regarding the interaction and integration of the problems and disciplines represented within the SRC. Our research has revealed that systems science and engineering is a powerful unifying, interdisciplinary approach to engineering design problems. Our focus on automatic control and communication systems amplifies this point further. We found that chemical plants and automated printed circuit board factories need the same hierarchical, multi-time-scale decision aids for scheduling, planning, operations, and even design. Large, flexible space structures and highly dexterous advanced robotic arms and hands need the same laboratory/design environment and can benefit from sophisticated theories and software systems analyzing multibody dynamics and distributed sensor fusion. Computer and communication networks, on the one hand, and flexible manufacturing factories, on the other, can benefit from the system-level design tools for modeling, simulation, and performance evaluation that we are developing. Polymerization reactor control and sequential target discrimination rely heavily on our ability to design digital, real-time, nonlinear estimators. Design of unusually large VLSI chips and the integration of CAD with CAM both require the object-oriented data base management and control schemes that we are developing. As we continue our efforts at the SRC we expect this vast cross-fertilization to guide us in the creation of the design tools for tomorrow's systems.

THE EDUCATIONAL PROGRAM

The educational program of the SRC is aimed at developing undergraduate and graduate curricula with emphasis on the five focus technical areas of the Center. This program complements the research activities of the Center and reflects our commitment to developing an extensive and continuous exchange of educational information with other universities and research institutions, private industry, and government research and development (R&D) laboratories.

Of particular concern in the development of the educational programs of the SRC is the planning and timing of specific courses targeted at bringing the advancements in AI, VLSI, and CAE to many undergraduate and graduate students. This is critical in order to create the necessary "technologically literate" student core for the SRC programs. Special purpose courses on AI will be offered in the fall semester of 1986 in four separate sections (in the electrical, mechanical, chemical engineering, and computer sciences departments) at the sophomore and junior levels. In addition, a graduate course/seminar on AI tools will be given from the Applied AI Laboratory, which is currently under development.

The SRC is rapidly developing plans for a specialized program of short courses that will bring state-of-the-art research results to industrial research scientists. This program will be an SRC-wide extension of the very successful short course on chemical process control offered by the Chemical Engineering Department. These courses will be sponsored by SRC and will bring, as speakers, authorities on various subjects of interest to SRC, both from faculty affiliated with SRC and elsewhere.

In addition, we have initiated the sponsoring or cosponsoring of colloquia, workshops, satellite video conferences, and symposia to facilitate the educational function of the Center.

I would like to briefly describe the highlights of what has been achieved to date. Further details can be found elsewhere (Systems Research Center, 1985, 1986).

- We initiated a shift to AI language programming from FORTRAN. As explained earlier, we believe that AI languages offer many advantages for the description and resolution of engineering design problems.
- We introduced or modified some 20 engineering courses, with particular emphasis on VLSI, AI, and CAE technologies.
- We sponsored a variety of interdisciplinary systems colloquia, including weekly colloquia for SRC students.
- We emphasized undergraduate research projects and facilitated the necessary matching between faculty and students. Students were strongly encouraged to build real systems.
- We established procedures for coadvising and joint teaching, breaking several cross-departmental boundaries.
- We established an advanced design laboratory for college-wide classroom use. Optimization-based design and other advanced software tools will be introduced to students.
- By insisting that the students actually go through the design process, we have increased student awareness of implementation and digital design issues.
- We created a distinguished graduate and undergraduate SRC fellowship program, with explicit industrial connections. We try to provide the student with an industrial mentor, in addition to his or her academic adviser.
- We facilitated student visits and residency at industrial sites. Seven graduate and four undergraduate SRC students spent part of summer 1986 on internships with industrial or government R&D labs.

THE INDUSTRIAL COLLABORATION PROGRAM

We are grateful to many corporations and government laboratories for a plethora of technical exchanges and joint projects, as well as for support received in the form of funds for faculty and student activities, unrestricted funds, and equipment gifts. We are pleased with the developments to date and look forward to even more interactions during the second year. From the description of the research program given above it should be obvious that we are developing a long-range, deep collaboration program with industry and government. The students have played a key role here. We basically followed our plans delineated elsewhere (Baras, 1986; Systems Research Center, 1985, 1986) and put primary emphasis on the development of strong technical ties between SRC researchers and industry and government scientists and engineers. In the limited time and space available here, I would like to describe the highlights of the program to date.

- We had numerous technical contacts, ranging from full-day meetings to shorter visits. As a result, many joint projects have been initiated.
- We created an endowed SRC fellowship program that proved to be extremely attractive to industry. Sponsorship of students provides an extremely robust and strong link with industry.
- Several technical advisory committees have been established, and we formed the SRC Research Advisory and Administrative Councils.
- We have received support from industry by means of a relatively unstructured and flexible program, given the time delays necessary to establish more formal schemes. We are currently formalizing many of these relationships along the lines of our planned industrial affiliates program (see Baras, 1986), with its three-tier structure. We anticipate that by September 1986 we will have formal agreements with at least three corporations at the highest (sustaining partner) level, with at least two corporations at the middle (sponsor) level, and with at least 10 corporations at the basic (associate) level.
- We have initiated strong collaborations with NBS, NRL, NASA, and NIH on a variety of interdisciplinary research projects.
- To date, the following corporations have provided support to the SRC. *Affiliates:* Applied Technology Inc., ARCO Chemical Corporation, Control Data Corporation, Digital Equipment Corporation, E.I. Dupont de Nemours & Co. Inc., Eastman Kodak, Exxon Corporation, Foxborough Inc., Grumman Aerospace Corporation, Martin Marietta Corporation, Mobil Oil Corporation, Rexnord Inc., Sperry Corporation, Texas Instruments Inc., Westinghouse Electric Corporation. *Equipment donors:* Application Engineering Corporation, AT&T, Cincinnati Milacron, Con-

trol Data Corporation, Data General Corporation, Digital Equipment Corporation, Intel Corporation, Kinetic Systems Corporation, Lisp Machine Inc., Moldflow Australia, Silicon Graphics, Sun Microsystems, Symbolics Inc., Texas Instruments Inc., Valid Logic Systems.

A PREVIEW OF THE SECOND YEAR

Our plans for the second year call for continuation of our efforts along the same lines with emphasis on the following. In the research program, pursue more intellectual integration and the formal initiation of the software "club"; in the educational program, develop short courses with industry, increase industrial participation in teaching, initiate the lecture note series and the technical magazine, and provide new integrated design courses and projects; in financial support, diversify further with other federal, state, and industrial sources; in facilities, move into a new 26,000-sq.-ft. building and continue development of the SRC constituent laboratories—VLSI Systems Design Lab, VLSI Systems Testing Lab, Process Systems Lab, Computer Integrated Manufacturing Lab, Intelligent Servomechanism Lab, Applied AI Lab, Signal Processing Lab, Computer and Communication Network Lab, Computer-Aided Design Lab, and Advanced Robotics Lab.

(For further information regarding results presented here, including technical papers and reports, software, etc., please contact: Mr. Timothy McGraw, Assistant to the Director for Information Dissemination, Systems Research Center, University of Maryland, College Park, Building 093, College Park, Maryland 20742; telephone: (301) 454-6167.)

REFERENCES

Baras, J. S. 1986. Systems Research Center. Pp. 61-74 in *The New Engineering Research Centers: Purposes, Goals, and Expectations*. Washington, D.C.: National Academy Press.

Systems Research Center. 1985. Report for the period May 1, 1985, to January 31, 1986, submitted to the National Science Foundation November 15, 1985.

Systems Research Center. 1986. First Annual Report, August.

ACKNOWLEDGMENTS

I would like to thank all SRC faculty, students, and staff whose accomplishments I described here. In particular I would like to thank my colleagues R. Brockett, K. Y. Choi, N. Farvardin, G. Harhalakis, J. Ja'Ja', P. S. Krishnaprasad, M. Pecht, S. Shamma, and A. Tits for their help in the preparation of this paper. Special thanks are also due to SRC staff members Pamela Harris and Pari Noskin for their tireless and efficient efforts in the preparation of this paper and the symposium presentation.

DISCUSSION

One listener expressed concern that foreign-born students educated in the Center might return to their home countries, taking ERC technology and ideas with them. Dr. Baras expressed his opinion that this would not be a problem as long as the United States remained competitive and provided a challenging and attractive working environment for top engineers. He said that the program of international collaboration being run by his Center with scientists and engineers from other countries was a productive, two-way cooperation. To another question regarding the range of apparently disparate applications of Center projects, Dr. Baras emphasized that the objective is to develop a common set of system-level design tools that can be applied to virtually any application. "We are trying," he said, "to investigate systems science and engineering itself, not the particular manifestation peculiar to a given application."

Engineering Research Center for Intelligent Manufacturing Systems

JAMES J. SOLBERG

INTRODUCTION

After a year of operation, the Purdue Engineering Research Center (ERC) has already established the validity of the concepts that motivated the ERC program. Much is at stake in this "quiet revolution" that we all hope will enable American industry and universities to respond to the demands of a changing world. At Purdue University we are grateful for the opportunity provided by the National Science Foundation (NSF) to participate in the ERC program, and I am happy to report that the experiment so far seems to be working.

It is understandable that a new Center would be preoccupied initially with the organizational details that necessarily accompany the formation of any large-scale effort. Happily, we have grown out of that stage and in recent months have been able to concentrate on more substantive issues. Consequently, this report will emphasize accomplishments. For information about the philosophical and organizational aspects of the Purdue ERC, the interested reader may refer to the report that was prepared for last year's symposium (National Research Council, 1986).

Following a very brief statement of the mission and scope of our ERC, the activities of the past year will be described in three sections: research, education, and industrial interaction.

Although, for the sake of orderly discussion, these aspects will be described separately, it is important to realize that all three are tightly integrated. Indeed, one of the key distinguishing features of the ERC concept was to achieve this coupling. We have succeeded in this goal to the extent that it is now difficult to categorize many of our activities as belonging to one or another section.

MISSION AND SCOPE

The broad goal of the Purdue ERC, as it is for all ERCs, is to "stimulate development of fundamental knowledge in engineering fields that will enhance the international competitiveness of U.S. industry and prepare engineers to contribute more effectively through better engineering practice."*

The particular sector of industry that we address is that which deals with discrete product manufacturing. In terms of the Standard Industrial Classification codes, we focus on those that fall in the range from 34 through 39, representing about 57 percent of the dollar value of all manufacturing, or about 12 percent of the gross national product (U.S. Department of Commerce, 1986). The full range of manufacturing activities, including everything from product conception through shipment, is within our scope of attention.

The unifying focus for the research program of the ERC is to lay the foundations for the total system of a new generation of discrete product factories, leapfrogging the current and developing generations, and to develop a methodology for designing and operating them. We call this new generation of technology *intelligent manufacturing systems*, a phrase intended to describe a higher order of automated design/manufacturing systems than any now known. They will be fully integrated, flexible, self-adaptive, computer-controlled systems covering the full range of factory operations from product conception through delivery. The emphasis upon systems is intended to address the need for better coordination of the various technologies involved in modern manufacturing. The use of the word *intelligent* is intended to convey the concept of a system that is able to adapt itself quickly and economically to changes in requirements and unpredictable events.

---

* From the NSF Program Announcement for Engineering Research Centers.

This long-range vision serves as the distant beacon to keep all of our efforts directed toward the same end. In practice, much of our work is directed at shorter-range objectives, which can deliver usable results within a year or two. This is highly appropriate, considering the urgent needs of U.S. industry to survive the next few years with enough residual strength to make the transition to a more advanced technology. However, it is important to make those step-by-step advances in harmony with a larger plan. We are convinced, both from our own study of the issues and from detailed discussions with many people in industry, that we have identified a major opportunity for the kinds of improvements in manufacturing that will be necessary to compete in the world of the next century.

RESEARCH

The research program is organized into eight technical thrust areas, each of which is based upon a problem—rather than a discipline—orientation. The eight areas are design, process planning, fabrication, system control, transport, communications, sensing, and assembly. These eight areas seem to provide a framework for all the work we contemplate, although it is possible that we may have to create a new area if the need develops. Of course, it must be understood that the words used have a broad meaning. For example, *system control* can refer to very high level factory controls as well as to low-level device controls.

Each thrust area is addressed by a cross-disciplinary project team, as shown in Figure 1. The 31 professors indicated in this chart, along with the 84 graduate and 30 undergraduate students, provide the building blocks for the eight thrust areas, which in turn make up the singular objective of the intelligent manufacturing system. In every area, the objective is to achieve innovations that advance the individual area, while at the same time advancing the overall system concept.

As Figure 1 indicates, there are many cross-connections to ensure communication among the thrust areas. In addition to regular meetings within teams, a biweekly meeting of the entire group of faculty and a biweekly meeting of the entire group of students further ensure this essential communication. A research panel, which meets for two hours every week, serves to provide the overview.

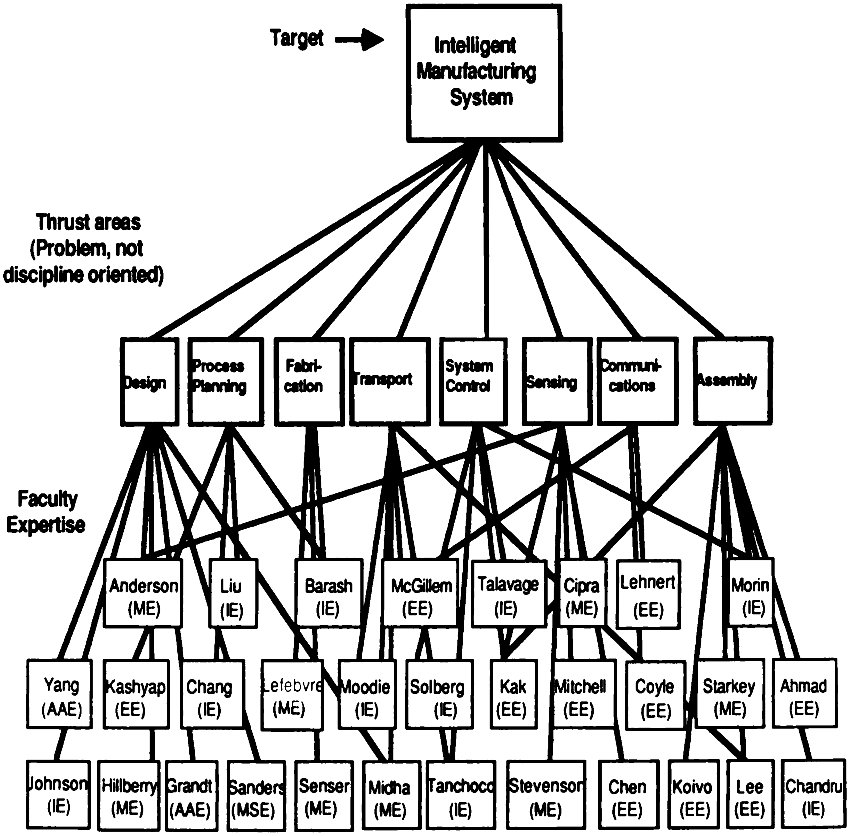


FIGURE 1 The thrust areas and teams. Abbreviations: ME, mechanical engineering; IE, industrial engineering; EE, electrical engineering; AAE, aeronautical and astronautical engineering; MSE, materials science and engineering.

An indication of the general flavor of the projects at a somewhat more detailed level is conveyed by the titles of current projects:

Projects in Design

- Computational geometry of surface intersection
- Solid modeling and feature representation
- Integration of finite element modeling
- Executive system for computer-aided design (CAD) modeling
- Integration of materials design into CAD

- Shape understanding and data base design

Projects in Process Planning

- Architecture for distributed process planning
- Intelligent distributed data base with reasoning capability
- New knowledge representation tools for process planning
- Modules for selected machining and nonmachining processes
- Automated numerically controlled tool program generation and verification
- Feature extraction for tool and process selection

Projects in Sensing

- Precision noncontact measurements
- Range mapping and interpretation
- Partial shape recognition
- Generic shape recognition
- Gray scale morphology implementation
- Surface texture analysis
- Vision-guided servoing

Projects in Assembly

- Theory of two- and three-fingered grasping
- Automatic assembly task planning
- Pipelined architecture for kinematic control
- Knowledge-based robotic assembly cell
- Multiple manipulator coordination
- Optimal task assignment and sequencing
- Sensor-based collision avoidance

Although these lists are incomplete and cover only half of the thrust areas, they do give some idea of the general nature of the activities under way. Of course, many other people at other universities or research laboratories are working in the same or similar areas. To understand the unique approaches taken within any project requires a more detailed explanation, which could not be attempted in the space available here. An annual report containing an abstract for each project is in preparation, and will be made publicly available in September 1986.

A few words about our research facilities are in order. Figure 2 shows the major pieces of equipment in the ERC laboratories. What is particularly significant about this figure, aside from the sheer quantity of equipment, is that it is all linked. We know

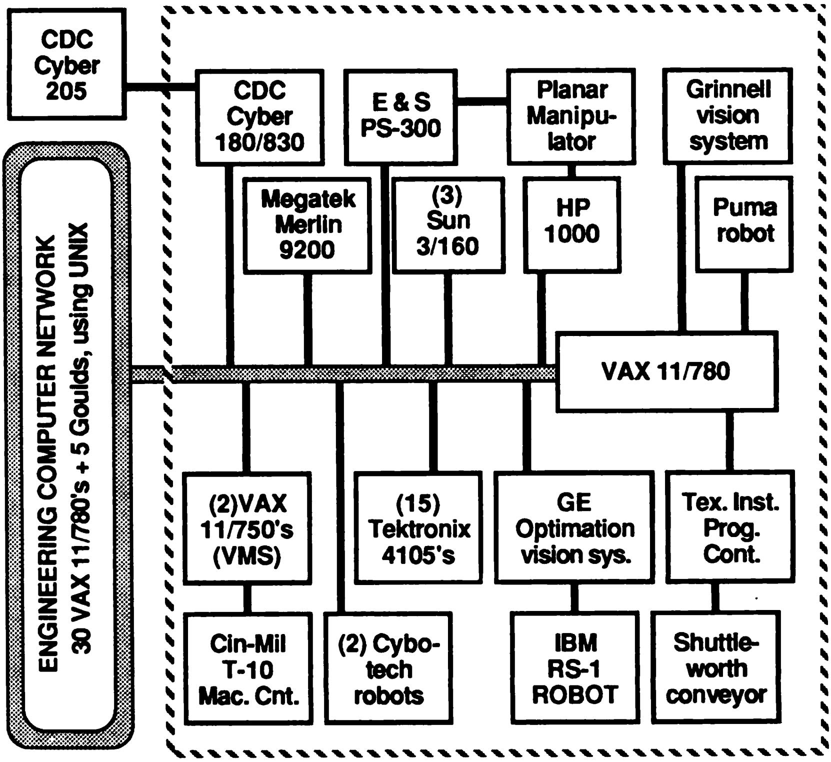


FIGURE 2 The equipment network.

of no other university computer-aided design and manufacturing (CAD/CAM) laboratory facilities that have achieved this degree of integration. Although it is no one person's responsibility and cannot even be classified as a research project, it is nevertheless a considerable technical achievement to have created this environment for research.

EDUCATION

Purdue University granted a total of 1,790 engineering degrees (B.S., M.S., and Ph.D.) in the 1984–1985 academic year, more than any other university in the United States (Ellis, 1985). The size of the educational program offers both the challenge of overcoming massive inertia and the potential for enormous impact. Through the indirect effects of changes in the basic curricula of (primarily) electrical, industrial, and mechanical engineering, we hope to influence the education of nearly 1,000 students per year.

For the past decade or two, engineering curricula have tended to emphasize methods of analysis; the basic approach to complex problems has been to break them down into their components and to study these in detail. The engineer that will be needed in tomorrow's industry must have strong skills in synthesizing technical knowledge. The increasing complexity of systems and the importance of systems behavior compel a new emphasis on understanding the interactions among components. The curriculum revisions now under way reflect this change in emphasis.

In the past year, as a direct consequence of the ERC activity, 12 new courses were created, all but one of which have now been taught for the first time. The course numbers and titles are as follows:

EE 595	Expert Systems
EE 595A	Real Time Robot Control
EE 595K	Sensor-Based Robotic Systems
EE 562	Computer Data Management and Artificial Intelligence
EE 695	Control of Robotic Manipulators
IE 584	Integrated Material Handling Systems
IE 590A	Topics in Computational Geometry
IE 670	Concentrated Energy Beams Processing
IE 690	Design, Manufacturing, and Artificial Intelligence
IE 690X	Information Dynamics
ME 463	Engineering Design
ME 597R	Analysis and Design of Robotic Manipulators

Two of these courses—EE 595K and ME 597R—were the subject of a unique educational experiment. Under a supplementary grant from the National Science Foundation, these courses were designed to involve representatives from industry directly in the classroom. Industrial participants in this effort included representatives from Allen-Bradley, Allison, Cincinnati Milacron, Cybotech, Ford, GMF, General Motors Tech Center, and McDonnell Douglas. The idea was to expose students to the kind of "real world know-how" that only comes from industrial practice. Engineers brought to the classroom not only their personal experience but also videotaped examples and even physical equipment. The experiment was judged to be highly successful by the students, by the professors, and by the industrial participants. The courses will be repeated.

The same educational experiment had an interesting sequel. During the summer, a two-week institute was conducted for the benefit of faculty and students of other universities interested in teaching in the area of robotics and automation. A total of 40 faculty and students from 20 universities attended. The subject matter and form of presentation were the same as had been worked out for our own students. The industrial representatives returned with their now-refined presentations. Again, the experiment was judged to be highly successful by all concerned.

The entire two weeks of presentations and discussion was captured on 65 hours of videotape. The plan is to edit the program to perhaps 40 hours, and then to distribute the tapes to any university interested in acquiring these educational materials. The National Technical University (NTU), of which Purdue is a member, provides one possible distribution channel.

In another unique program which is intended to fulfill both research and educational objectives, the ERC offers to qualifying students the opportunity to become Summer Undergraduate Research Interns (SURIs). Thirty students were selected to begin work during summer 1986. Each of these students joined an already established research project team consisting of faculty, graduate students, and industry representatives who had been working throughout the year. They were paid for their work, and they made a real contribution to the effort; they were not just a token presence. We were successful in attracting highly qualified students. Their median grade point average was 5.6, and several had a straight 6.0.

The real purpose of the program is to provide a genuine research experience for some of the best undergraduates—something that is normally not available at the undergraduate level. It is hoped that many of these students will enjoy the experience enough to consider staying for graduate work. In any case, they will have obtained an exposure to the methods of advanced research, so that later in life they will have a better understanding of what it takes to achieve technical innovation in the modern world.

Perhaps the greatest educational impact occurs through those graduate students who are directly employed in the research work. Those who enter the program now will probably never realize

TABLE 1 Distribution (number) of ERC Students Across Departments

	Department[a]				
Level	EE	IE	ME	Other	Total
Ph.D.	22	12	9	4	47
M.S.	7	11	16	3	37
B.S. (SURIs)	12	8	9	1	30
Total	41	31	34	8	114

[a]Abbreviations: EE, electrical engineering; IE, industrial engineering; ME, mechanical engineering.

how different their graduate studies are from what they would have been only a few years ago. In particular, the degree of cross-disciplinary communication that is taken for granted now did not exist except by the accident of chance acquaintances. An indication of the present situation can be obtained from the distribution of the ERC students at various levels from different schools, as shown in Table 1.

INDUSTRIAL INTERACTION

The fulfillment of the mission of the ERCs requires the direct participation of industry. The identification of critical research needs and the development of appropriate educational programs and more effective means of technology transfer (in both directions) all point to the vital necessity of establishing very close working relations with industry. In fact, none of these could be properly addressed without the involvement of industry. The arrangements for industrial involvement in the Purdue ERC are given in another paper in this volume (see J. J. Solberg, "Highlights of the Interaction with Industry: The Engineering Research Center for Intelligent Manufacturing Systems," Part III).

CONCLUSION

The first year has been one of gratifying progress toward the achievement of the goals set out when the ERC program was established. The enthusiastic cooperation of many people was essential in achieving this progress. The fact that so many people were ready to join the effort is testimony to the belief that the time is right for the ERC concept. Thus, although a monumental effort still lies ahead, we have every reason to be hopeful that the ERCs can play a profoundly important role in restoring competitiveness to American industry.

REFERENCES

Ellis, R. A. 1985. Engineering enrollments, fall, 1984. Engineering Education 76(Nov.):102-108.

National Research Council. 1986. The New Engineering Research Centers: Purposes, Goals, and Expectations. Report of the Cross-Disciplinary Engineering Research Committee. Washington, D.C.: National Academy Press.

U.S. Department of Commerce, Bureau of the Census. 1986. Statistical abstract of the United States, 1985. Washington, D.C.: U.S. Government Printing Office.

DISCUSSION

Dr. Solberg was asked about the difference between industrial member and affiliate status. He explained that there is a quantum difference in level of support and participation (see J. J. Solberg, Part III). Regarding the proportion of industrial commitment obtained prior to selection as an ERC, Dr. Solberg pointed out that the structure of the pre-existing Computer-Integrated Design, Manufacturing, and Automation Center (CIDMAC) provided an invaluable base of experience as well as actual support.

Center for Robotic Systems in Microelectronics

SUSAN HACKWOOD

INTRODUCTION

When the National Science Foundation (NSF) initiated the Center for Robotic Systems in Microelectronics (CRSM) as one of the first Engineering Research Centers (ERCs) just over a year ago, the general charter we were given was to create a center of excellence in an academic environment that would lead to the increased competitiveness of U.S. industries. The Center was to provide facilities for fundamental and applied research, with a special interest in *cross-disciplinary* research, education, and technology transfer to industry.

Having just arrived from industry, the Center's founders started completely "from scratch." In retrospect, this was an advantage, for we therefore had much more flexibility and fewer constraints in shaping our program. The original commitment from NSF to CRSM was for $14 million over a five-year period. The commitments from the University of California at Santa Barbara included start-up equipment funds and our current facilities (15,000 sq. ft. of laboratory space and a 1,400-sq.-ft. class 100 clean-room). Additional commitments for 1986 include support for new laboratory space, the hiring of faculty, and the University of California system-wide support of our new mechatronics program.

Our growth in the first year has been exponential. Numerous research programs have been established, an educational program has been initiated, and new industrial partners have joined our program. We have developed new approaches to systems research, to industrial collaboration, and to international cooperation. Our predictions for 1986 are for continued growth, with emphasis on research excellence.

The research goals of the CRSM are to design, build, and install robots and robotic systems for the microelectronics industry. Our approach to this goal involves (1) the establishment of a center of excellence in robotics research and (2) the establishment of a robotic systems "clinic" for developing university-industry cooperative projects. We are also actively pursuing the creation of new knowledge by generalization from specific tasks to fundamental or generic principles.

The research direction of the Center is toward the development of advanced robots capable of high precision and high-speed motion. These robots are designed to operate in specialized environments, such as in a clean-room or in a vacuum chamber. The subject areas we specialize in are mechatronics, intelligent machine perception, and robot system design. I will review some of our initiatives in these areas and describe the future directions of our research.

THE RESEARCH PROGRAM

The CRSM conducts cross-disciplinary research in robot system design and innovative flexible manufacturing processes. Currently involved are 16 faculty members, 7 visiting researchers, 4 research engineers, and over 40 graduate students from the Departments of Electrical and Computer Engineering, Mechanical Engineering, Computer Science, and Chemical Engineering. We also have 10 undergraduate students employed as technicians. The CRSM has a charter to develop automation technology for the microelectronics industry. As was just mentioned, we are particularly concerned with designing and building high-speed, high-precision, intelligent robots. Basic and applied research in robot mechanics, computer control, and machine perception is conducted with a strong emphasis on system integration.

Our research covers three broad areas: (1) advanced mechatronics, (2) machine perception and intelligence, and (3) robot system design for microelectronics. To give the reader an idea of our areas of interest, some of our recent research accomplishments are outlined below.

Advanced Mechatronics

1. Designed and built a prototype five-bar linkage direct drive arm. Key features:

- Clean mechanisms: designed to be used in class 100 clean-room
- Remote actuators: motors mounted away from hand allow clean operation
- High precision: designed for 1 μm accuracy
- Carbon fiber structure: designed for high acceleration ($3g$)

2. Designed and built high-speed digital motion controller based on a digital signal processing integrated circuit. Key features:

- High update rate: >100 KHz
- Capable of controlling fast, precise robots
- Capable of adaptive control algorithms

Future Directions

- Design of programmable multiprocessor controller-based CORDIC systolic arrays
- Design of robots for operation in high vacuum
- Control of flexible robots

Machine Perception and Intelligence

1. Designed and implemented expert system for multisensory input from complex materials processing machines. Key features:

- Expert system monitors semiconductor fabrication equipment
- Improves upon Mycin-type expert systems

2. Applied color vision to oxide thickness measurement. Key features:

- Measurements can be carried out in situ
- Measurements accurate to <30 Å
- Measuring equipment is inexpensive

3. Developed new algorithms for color vision processing.

4. Set up a mechano-optics laboratory. Key features:

- Advanced sensor systems
- Micropositioning using holography

Future Directions

- Develop self-learning and adaptively controlled robots
- Develop hierarchical, rule-based system for process control and machine diagnosis
- Conduct basic research on the application of color vision to automated inspection processes

Robot System Design for Microelectronics

1. Designed and built fiber-optic alignment workstation. Key features:

- High precision: 1 μm
- High-speed search algorithms

2. Designed and built laser chip-mounting workstation. Key features:

- High precision: 2 μm
- Self-contained workcell integrating vision and mechatronics

3. Process control for microelectronics. Key feature:

- Automated adaptive control of oxide growth on silicon

4. Started Automated Guided Vehicle Program

Future Directions

- Develop self-navigating mobile robots
- Design a robot workstation for precision assembly

EDUCATIONAL PROGRAM

We have initiated a teaching program at both the graduate and undergraduate levels. A three-quarter, senior-level undergraduate program in robotics has been initiated, and a graduate sequence is being implemented. Two graduate courses are already being offered, and the other is offered in an independent study format. The program includes not only new course material but also new methods of teaching. Two key ingredients of the program are the focus on System Design and Mechatronics.

System Design

The System Design program begins at the undergraduate level. In addition to course work, students participate in an Industrial Telepresence in Robotic Systems Education (ITIRSE) program. The ITIRSE program is aimed at facilitating the flow of relevant industrial knowledge to engineering schools. It involves a weekly seminar series with a company and is offered to all students participating in the CRSM. If successful, the program will be introduced as a normal part of the graduate and undergraduate curriculum upon approval by the College of Engineering Curriculum Committee.

The goal of ITIRSE is to expose the students to knowledge beyond the experience of or not readily available to faculty members, nor accessible from textbooks, and to allow access to facilities and equipment not available at the university. The best way for the students to obtain this knowledge is to spend time on site in the industrial environment. If direct experience on site is not always possible, an alternative method is to have a two-way video and audio link between university and industry. ITIRSE uses five communications components:

1. two-way audio link using speakerphones for teleconferencing;
2. video playback of prerecorded operations;
3. two way real-time drawing link using facsimile machines;
4. hard-copy whiteboard for group design; and
5. a photo-phone link which can transmit still video images over the phone lines at 9,600-baud rate.

We use these five components to establish an interactive systems design link between industries cooperating with the CRSM and students participating in the CRSM educational program. The emphasis is on design because it is in this area that industrial expertise is most valuable and most difficult to communicate.

Several companies associated with CRSM participate actively in ITIRSE and provide some support for the program. Prominent among them are GMF, Delco Electronics, Plesscor Optronics, and Bell Communications Research. The companies benefit from this interaction as they get to know students and can influence research projects. A secondary benefit of the program is that the company has the necessary equipment in place to participate in other seminars held at the CRSM. For example, visiting speakers from other institutions may be audited at the company location.

Mechatronics

The Mechatronics Program is aimed at educating engineering students in mechatronics—i.e., in the technology of microprocessor-controlled machines. This technology, which has evolved over the past 15 years and has attained its highest level in Japan, is crucial to increasing U.S. competitiveness in world markets. Realizing that U.S. colleges and universities are seriously deficient in educational programs centered on this technology, we have created the Mechatronics Program to match similar programs that have been in existence at major Japanese universities for more than a decade. The topics that constitute mechatronics (taken from a series of Japanese texts in mechatronics) are (1) control by microprocessors, (2) electromechanical machinery and control, (3) actuators, (4) electromechanical interfaces, (5) sensors, (6) manipulator control, (7) mechano-optics, and (8) manufacturing systems.

In the United States mechatronics is still viewed as something to be left to the factory floor engineer, outside of the academic world. American universities do not have departments specializing in precision engineering, manufacturing, and mechatronics. Moreover, most mechanical engineering departments emphasize *analysis* of mechanical structures while paying little attention in research or education to the *design of mechanisms*—a central aspect of mechatronics.

The lack of emphasis on and training in the manufacturing sciences has recently become a subject of increasing national concern. This lack may be due, in large part, to the prevalence of attitudes by which manufacturing implementation is considered to be neither a science, nor difficult, nor worthy of consideration—certainly in an academic environment. It may well be that it is precisely because of this attitude that the United States has continued to lag behind Japan in improving manufacturing productivity, in spite of the vast resources poured into robotics research in many American universities. Students are being trained in some aspects of robotics, but not in mechatronics. Consequently, we cannot compete with Japan in the design of reliable, precision machinery.

Indeed, in the United States, it is difficult to find experts in these fields in academia or industry. To remedy this situation, CRSM is creating a new program, the first in the United States dedicated to mechatronics education.

INDUSTRIAL PARTICIPATION

Industrial participation is key to the success of the CRSM, as our research directions are inspired by industrial needs. We currently work with over 20 companies including AT&T Bell Laboratories, Airco Temescal, Bell Communications Research, Delco Electronics, GMF Robotics, Hughes Aircraft, IBM, Intel Corporation, Intelledex, Microbot, MacDonnell Douglas, Plesscor Optronics, Rockwell International, Santa Barbara Research Center, the Semiconductor Research Corporation, Sputtered Films, Varian, and Xerox. Companies can work with us in a number of ways; they can join a sponsor's program, an affiliates program, or the Robotic Systems Program. Companies involved with systems projects include Delco Electronics, GMF Robotics, Bell Communications Research, Intel, Airco Temescal, Plesscor Optronics, Rockwell International, and Sputtered Films.

FUTURE PLANS

We are confident that the CRSM will experience rapid growth over the next four years. A synopsis of anticipated developments follows.

In 1986, the CRSM further developed the areas of innovation that it initiated in 1985. The five areas are:

1. research in robotics for microelectronics;
2. new method of university-industry research;
3. the mechatronics program;
4. the "Bridge from Japan"; and
5. utilization of para-engineers.

Research in Robotics for Microelectronics

The CRSM has pioneered research in key areas crucial to the application of robotics to microelectronics. Research groups and facilities have been established. Through these we have conducted preliminary, basic work on and have built prototype models of robotic systems that will perform rapidly, accurately, and cleanly. That work allows us to forecast significant developments in the following areas.

Clean robotic mechanisms will undergo significant development during the next few years. A second, related area of research is in the utilization of composite materials for robotic structures. Prototypes have been designed and built, as described earlier on under "The Research Program." Results thus far have been so promising that we anticipate the generation of significant, basic advances in robotic architecture. Our design and testing facilities are being expanded during 1986. We hope that a collaboration with the ERC at the University of Delaware during 1986 will be fruitful, so that research on the fundamental materials aspects of composite structures need not be duplicated.

Encouraged by this year's success in research on digital motion control, we intend to further expand the scope of that research. We are currently designing controllers for high-precision robots and implementing them in very large scale integrated (VLSI) circuit manufacturing.

Work performed on the application of color vision to microelectronics processing has already indicated that the enhanced (with respect to black and white) resolution and sensitivity of properly constructed color vision systems can offer significant improvements in speed and resolution of inspection and process control in microelectronics fabrication. Progress has already been made in fundamental aspects of color vision (e.g., data processing). This basic research will continue, as will consideration of color vision instrumentation suitable for microelectronics.

Research in intelligent monitoring, control, and diagnosis of complex machines doubled in volume in 1986. We are in the process of implementing systems that will take in and reduce data from multidistributed machine sensors. We anticipate further development in the use and fabrication of various sensing elements.

During the first part of 1986 a new mechano-optics laboratory was built in which optical devices for robot guidance, sensing, and control can be investigated and enhanced. In addition, the facility will provide a capability for laser interferometry that will be used to develop (1) high-resolution positioning for precision mechanical motion and (2) optical holographic, nondestructive evaluation of materials.

We also anticipate that research in process control will begin to yield important results in the future. The expansion of this area depends upon the success obtained during 1986. A similar criterion will be applied to a number of fledgling research efforts that are now operating on a trial basis with low levels of support.

New Method of University-Industry Research

Robotic systems research at the CRSM is intimately related to the new method of research that the CRSM is pioneering. As we originally proposed to NSF, a program of both basic and applied research is being carried out. As a particular applied research problem is attacked, it serves as a catalyst to stimulate basic research. The use of applied research to stimulate basic research is the reverse of the traditionally followed method. Applied research constitutes only 25 percent of CRSM research, yet it is crucial for the generation of relevant and timely basic research.

One of our major goals is to continue to secure industrial support for systems projects that would serve as the catalyst for basic research. Based on our initial successes, we are confident that the new methods will prove both possible and productive. We have already completed two systems projects, and have received requests from industry to initiate three additional large-scale robotics systems projects. We consider the successful completion of these projects to be one of our highest priorities for 1986. Facilities, students, and technical support have been organized to accomplish this.

Since the systems projects, by their nature, require close interaction with the project company and immersion in the practicalities of the problems that they pose, they provide students with an unparalleled opportunity to acquire valuable skills, insights, and personal connections to industry. We therefore anticipate that an increased number of students will seek to work on systems projects.

As we increasingly gain the confidence of industry, we anticipate a corresponding increase in the participation of practicing engineers from industry. Several industrial engineers were in residence at the CRSM during 1986.

The Mechatronics Program

We anticipate official initiation of a mechatronics program during the next year. This program will probably increase by 20-25 percent the number of students participating in CRSM activities. We intend to build up closely linked educational and research laboratories that will also foster cooperation and support between undergraduate and graduate students.

We targeted mechatronics design as an area of growth for 1986. A mechatronics design laboratory is being established and equipped with mechanical and electrical components needed to facilitate the rapid design of prototypical new robot mechanisms. This approach closely follows Japanese "precision engineering" research and education programs that emphasize design.

The "Bridge from Japan"

One important area of innovation by the CRSM is its initiative to form a "Bridge from Japan." The word *from* is purposely chosen, to indicate that the information flow is expected to be primarily from Japan to the United States, rather than vice versa, as has happened too often in the past and is still happening in many American universities.

In June 1986, the CRSM added to its staff Prof. Yutaka Kanayama, formerly of Tsukuba University and one of only three Japanese robotics experts working in the United States. Four more Japanese robotics specialists are planning to join us as adjunct professors in the summer and fall of 1986.

The study of the Japanese language, especially written Japanese, will continue to be encouraged. Several students at the CRSM are studying Japanese, and one spent the summer of 1986 at a Japanese university. An important goal for 1986 is to initiate a strong exchange program with top Japanese institutions to join forces in mechatronics. (In this area the flux of information will definitely be to our benefit.) We feel that our establishment of a mechatronics program will provide a significant incentive to encourage our Japanese counterparts to join in the exchange with us. This initiative could pave the way to the formation of a binational (U.S.-Japanese) ERC in robotic systems and/or mechatronics.

Efficient Japanese translation remains one of our targets. In 1986 the CRSM will translate several full-length technical books and numerous articles and patents in the robotic systems area.

Utilization of Para-Engineers

A host of different skills and activities characterize the work of an engineer within the field of research carried out at the CRSM. Many of these activities are not strictly germane to engineering per se, in that they do not call upon conventionally defined engineering skills. The CRSM is striving to increase the productivity of each engineer by relieving him or her of any peripheral activity that can be performed by someone not formally trained in engineering. We call such persons *para-engineers*. Japan, for example, has 40 engineers for every 7 in the United States. Therefore, we believe that using American engineers to do engineering rather than peripheral tasks is imperative if we are to maintain the competitiveness of our industries.

During 1986, we will continue to develop areas of utilization for para-engineers, as well as to train personnel to be para-engineers. The university is an ideal environment for identifying and developing people with para-engineering talents. The structure of the para-engineering group, presently called TIO (Technical Information Office), will grow along three functional lines: (1) information collection, storage and retrieval; (2) worldwide communication; and (3) publication support and generation. For information collection, storage, and retrieval, we will have finalized and streamlined our data base facilities so that information on patents, papers, and relevant manufacturers is readily accessible. We intend to increase our video library to include 100 hours of technical reports, some of which will be generated through the ITIRSE program described earlier. For worldwide communication, we will establish the capability for efficient translation of Japanese technical papers and articles relevant to our field, and will also promote better communication with Japan. In addition, TIO will maintain a communications link with the top robotics research centers around the world. For publication support and generation, we intend to provide the human and technical resources that will facilitate documentation of research results, whether for internal memoranda or final papers for publication. Part of the work for publication support and generation also includes audio/video support (e.g., videotaping of experimental results) of research documentation.

In this manner, para-engineers will assist in virtually every aspect of research, from initiation and fact-finding to implementation to final documentation. Finally, we foresee that TIO will serve as the facilitator in the generation and submission of patent applications. Since the number of patents issued is a strong indicator of innovation in CRSM research, this latter function is highly important.

CONCLUSION

In this paper I have tried to briefly outline some of our goals and expectations. We feel we have come a long way in one year and are beginning to see many tangible results. The next few years are exciting and hold many promises as well as challenges.

DISCUSSION

Dr. Hackwood was asked whether the faculty of her Center had actively pursued summer internships at Japanese firms in the robotics field. She replied that the American faculty are reluctant to go to Japan because they do not speak Japanese, while Japanese engineers (who do speak English) are quite willing to visit the Center. Students are more willing than faculty members to study Japanese, so that more of them go to Japan. Regarding the question of proprietary status of technology under development in the Center's laboratories, Dr. Hackwood noted that she and her coworkers are trying to get more flexible university policies established in this area. For the present, they sometimes work on proprietary devices without letting the university researchers know the specific nature and purpose of the device, in order to allay industry concerns.

Center for Composites Manufacturing Science and Engineering

DICK J. WILKINS

INTRODUCTION

Before presenting the first year's progress report from Delaware's Engineering Research Center (ERC), I would like to tell a short story. I needed to be in Washington on May 1, 1985, for a business meeting, so I arranged to attend the symposium titled "The Engineering Research Centers: Factors Affecting Their Thrust," on April 29–30. I had represented the aerospace industry during the National Science Foundation (NSF) site visit to the University of Delaware during the ERC competition, was quite pleased with the outcome, and wanted to see how the ERCs would operate. In addition, my interest in engineering education was strong because one of my responsibilities at General Dynamics was to chair the Engineering Education Advisory Committee. The committee was chartered to suggest ways of teaching engineering, doing relevant university research, and preventing engineering obsolescence.

Thus, I found myself sitting on the front row at the ERC symposium. And what I heard was an incredibly enthusiastic series of speakers who convinced me that the ERC concept was the best cure for the ills of engineering research in the nation.

Subsequent events resulted in the University of Delaware ERC director, R. Byron Pipes, being named dean of the College of Engineering there. So when a national search began for his replacement, I was compelled to apply. Thus, my feeling of déjà vu was quite strong as I attended the second symposium and presented this paper.

My subject is the progress and impact of the Center for Composites Manufacturing Science and Engineering. It is a subject with which we at the Center are most familiar and most proud. I would like to depart from the standard format and summarize my presentation at the beginning.

Already, in 1986, we have satisfied some of our goals for 1990. Right now, for example, we count 42 undergraduate students working in the Center along with 71 graduate students. Both groups are larger than we had projected for 1990.

We have already captured all the funds needed to build and furnish our new building. All $5 million was pledged before construction even started.

We are exceptionally proud to announce the inauguration of the U.S. Army Center of Excellence for Manufacturing Science, Reliability, and Maintainability Technology. This center, part of Department of Defense (DOD) University Research Initiatives Program, begins a research thrust into the important area of reliability and maintainability of components in service. As such, it is an additional building block in the overall effort toward composite materials research at the University of Delaware, of which the ERC is a central component. The army program is expected to add $5.3 million in funding over the next five years. Consequently, we now expect our total annual budget for composites research to be about $5 million per year.

Now let me begin from the beginning. I will cover the history of the University of Delaware composites center, our cooperative programs, the research program highlights and plans, the academic program, and our important facilities plans.

HISTORY

Composites are defined as materials with two or more components that, in combination, yield properties such as stiffness-to-weight ratios that are superior to those of conventional materials. Current advanced composites typically employ high-stiffness or high-strength fibers (glass, aramid, carbon, or ceramic) embedded in a plastic, metal, or ceramic matrix.

The first academic course in composites at the University of Delaware was taught in 1969. This was only the third such course ever taught in North America.

In 1974, the Center for Composite Materials (CCM) was founded, with J. R. Vinson as director. The first of its kind in the United States, the Center emphasizes teaching and research. Its objectives are to:

- conduct basic research;
- provide prompt technology transfer; and
- train students for work in the composites field.

In 1978, the emphasis of the Center was expanded to include industrial interaction and technology transfer. R. Byron Pipes was named director.

In 1985, the National Engineering Research Center for Composites Manufacturing Science and Engineering was established by the National Science Foundation at the University of Delaware, with cooperation from Rutgers, the State University of New Jersey. Roy L. McCullough was named acting director of the ERC when R. B. Pipes was appointed dean of the College of Engineering.

In January 1986, I was appointed director of the overall CCM and a co-principal investigator, along with R. B. Pipes and R. L. McCullough, of the ERC program within the Center.

And, as I have noted, in June 1986 we were designated as the U.S. Army Center of Excellence for Manufacturing Science, Reliability, and Maintainability Technology. Tsu-Wei Chou and R. L. McCullough are co-principal investigators of the army program.

Figure 1 depicts our Center's organizational structure. The recent major changes in the organization have occurred at the top. We now have a dean of engineering who is totally committed to the concept of the ERCs, since he was the director of ours. It is also a big advantage for me as director to have come directly from one of the industries we are trying to serve. (I was the Engineering Staff Specialist for Composites Technology at General Dynamics in Fort Worth, Texas, where my team helped to develop composites technology over the past 17 years). I also have an appointment as professor of mechanical engineering at Delaware.

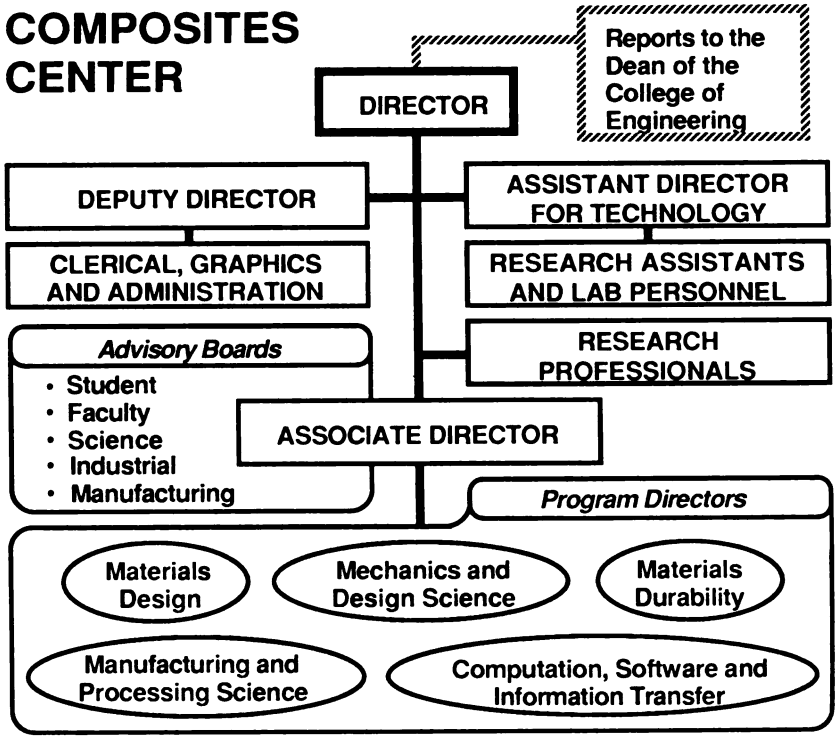


FIGURE 1 **Center organization promotes interaction and research.**

The business activities of the Center are managed by our deputy director, W. A. Dick, who has a support staff of about 10 people. They perform clerical, graphics, and administrative functions. The assistant director for technology, D. W. Wilson, manages our laboratories and equipment. He is also responsible for overseeing the numerous research assistants and laboratory personnel. At present, we also have eight additional research professionals who provide continuity and stability to our research programs.

Another key individual in our management scheme is R. L. McCullough, professor of chemical engineering, who serves as associate director of the Center. He interfaces with our various advisory boards and with the faculty leaders of the research program, the program directors.

Through our advisory boards, all of us in the Center exercise and improve our listening abilities. The Student Advisory Board provides a mechanism by which students can suggest ideas for improving the operation of the Center. The Faculty Advisory Board serves a similar function from the viewpoint of the faculty members whose students are funded by the Center, but also pays attention to our academic responsibilities. The Science Advisory Board, composed of experts in composites technology from around the world, keeps an eye on our long-range goals and scholarship. The Industrial Advisory Board, composed of two representatives from each company in our 35-company research consortium, meets with us regularly to recommend research thrust areas, technology transfer mechanisms, software needs, facility ideas, and a wide range of additional topics. The newest group, the Manufacturing Science Advisory Board, has two representatives from each of six companies in a special group that provides additional funds for equipment. This group advises us on the types of manufacturing processes that should be the subject of our research.

The program directors are faculty members who coordinate research efforts within and among our five research thrusts areas:

- Manufacturing and processing science—A. B. Metzner, chemical engineering, and R. B. Pipes, dean of engineering
- Materials design—R. L. McCullough, chemical engineering
- Mechanics and design science—T.-W. Chou, mechanical engineering
- Materials durability—J. M. Schultz, materials science, and I. G. Greenfield, materials science
- Computation, software, and information transfer—S. I. Guceri, mechanical engineering

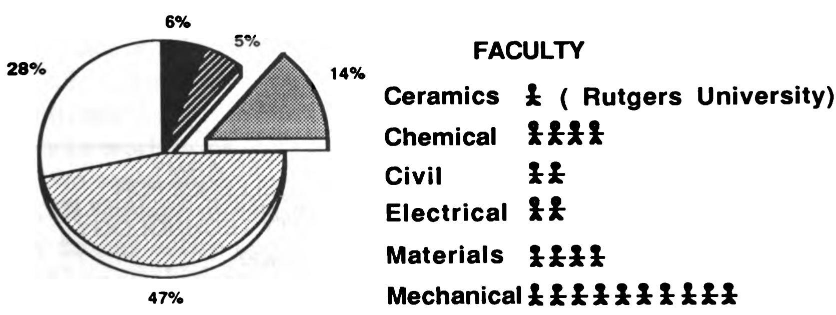


FIGURE 2 **The 23 faculty members represent six departments.**

Of our 150 people, fully three-fourths are students. And, as shown in Figure 2, our 23 faculty members represent six academic departments or programs. This statistic clearly shows the interdisciplinary nature of the Center's research.

COOPERATIVE PROGRAMS WITH INDUSTRY AND GOVERNMENT

The Center has a strong emphasis on interactive partnerships with business, government, and other universities. These partnerships are the subject of another paper in this volume, presented by W. A. Dick, deputy director of the Center. The various components of our programs can be understood more easily by referring to Figure 3. The NSF Center is a key element in our philosophy as well as our research, since this governmental partnership enables us to focus on the manufacturing aspects of materials which are critical to their production and use by U.S. industry.

As was mentioned above, our Center for Composite Materials began in 1974. The University-Industry Program entitled "Application of Composite Materials to Industrial Products" began in 1978. The growth of that program has been steady (Figure 4).

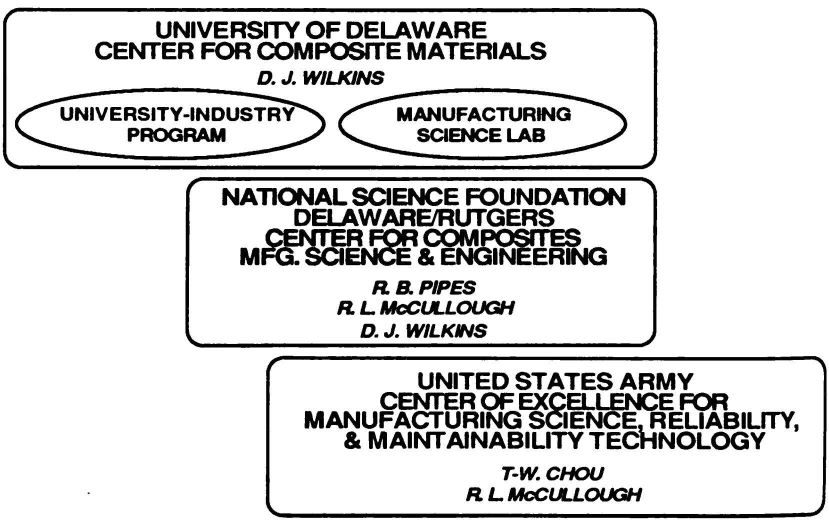


FIGURE 3 Center has several partnerships.

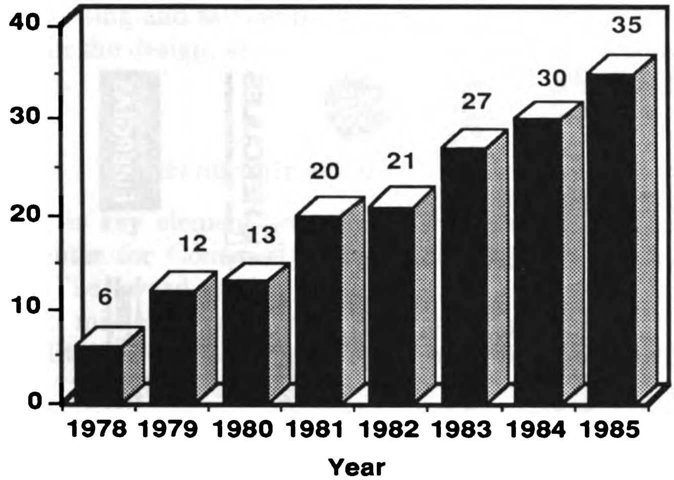


FIGURE 4 CCM university-industry program has enjoyed steady growth in sponsorship.

The 35 sponsors for the program year beginning 1 September 1985 (Figure 5) represent a broad, international spectrum of companies involved in the composites field. Of major significance to our research is the fact that the sponsors cover a broad range of interests, from the supplier side of the business to both the aerospace and automotive branches of the user community. This breadth of sponsorship allows us to uncover a wide variety of basic, fundamental problems with which to challenge our researchers. Given a choice, we prefer to solve problems that satisfy the needs of several companies simultaneously. The fact that our sponsors are worldwide means that our faculty and our students can truly put our work in global perspective.

Each sponsor company donates $38,000 per year to the research consortium. Our industrial partners receive a number of "deliverables" from the Center, ranging from research documentation to workshops to trained personnel. Each company is entitled to two seats on the Industrial Advisory Board.

It is clear to us that the University-Industry Program is the key to our entire operation. Without the insights into industry's problems, which leads to relevant research topics, which leads to useful results, which draws good students, etc., our program would clearly break down. With this program, we were able to develop

FIGURE 5 Sponsor companies of the University-Industry Research Program cover a broad spectrum.

good computing and testing facilities, which allowed us to become excellent in the design, analysis, and testing aspects of composites technology.

Partnership with Government

Another key element was the NSF award for establishment of the Center for Composites Manufacturing Science and Engineering. The award, which is the smallest of the ERC awards, is for $7.5 million over 5 years. Our strategy was to move beyond traditional engineering pursuits, on which we were already spending $2 million per year, into manufacturing by adding another $1 million per year. We and our industrial sponsors agreed that the barriers in composites technology must be expanded to include manufacturing issues. There were also problems that required interdisciplinary approaches and a systems-level viewpoint. Our academic partner, Rutgers University, contributes to an internationally known program in ceramics engineering, which has allowed us to move into research in ceramic matrix composites. This award gave us international visibility beyond our original sponsor group, and showed everyone that excellence can occur in medium-sized universities like ours, as well as in the large ones.

Soon after the inauguration of the ERC, we started the Composites Manufacturing Science Laboratory. When expansion and renovation are completed, the laboratory will house all the near-future manufacturing processes that our Manufacturing Science Advisory Board advises will be key to the future of composites manufacturing. Sponsor companies purchase two seats on the Manufacturing Science Advisory Board for five years by donating $100,000 to our equipment fund. This fund will ensure that we continue to replace equipment in the future.

The newest partner in the Center's research is the U.S. Army. The Center of Excellence for Manufacturing Science, Reliability, and Maintainability Technology will begin operation soon. It is funded for five years at about $1.1 million per year. This effort will build very logically on our design, analysis, testing, and manufacturing expertise to address the final component of the overall engineering problems, i.e., in-service reliability and maintenance.

The objectives of DOD's University Research Initiatives Program are to:

- improve research quality;
- strengthen multidisciplinary research for DOD;
- expand university-DOD interactions; and
- support fellowship and instrumentation awards.

The Center continues to seek active partners with whom to pursue mutual interests and needs. Over the next few years, we expect to spend in excess of $5 million per year on composites research.

RESEARCH PROGRAM PLAN

Our research is concentrated in the five thrust areas shown in Figure 1. We currently are supporting over 80 research projects in those areas. The way in which the areas interact with each other is suggested in Figure 6.

The *Manufacturing and Processing Science* area begins with commercially available reinforcements and matrix materials and investigates methods of producing defined microstructures. Some especially interesting results are being developed by Center researchers in computer-aided design of filament-wound composites, fiber orientation in fluid flows, laser tape consolidation, cure sensing of thermosetting polymer composites, nondestructive inspection, and comparable topics.

In filament winding, we are now able to predict the path of fibers around a nongeodesic shape. Such shapes are becoming

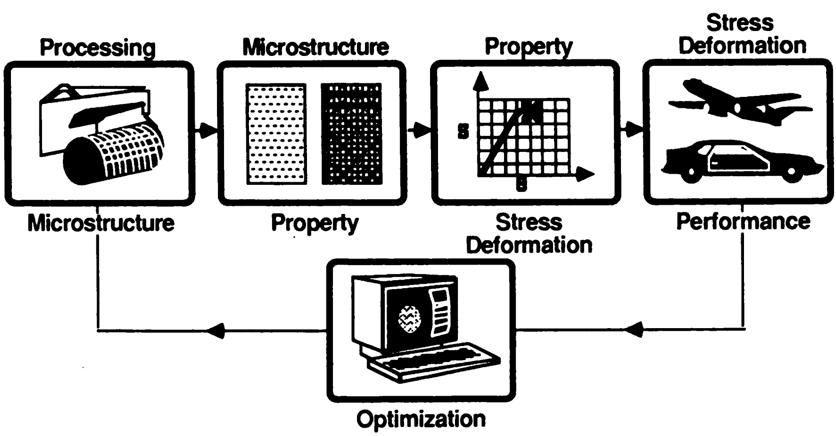


FIGURE 6 Center research is addressing key technical problem areas.

more common, and filament winding is applied to components of complex shape. The resulting stiffness properties can be predicted once the microstructure is defined.

Computer-aided design techniques are also being applied to the problem of fiber orientation in the mold filling of short fiber composites. Mold design can be greatly speeded up through the use of some of our new software.

We are continuing to explore the use of intermediate-power lasers to consolidate thermoplastic tape as it is automatically fed from a dispensing machine. Fundamental supporting research is being conducted in the area of melting, solidification, and crystallization kinetics of thermoplastic polymers.

In the field of thermosetting polymer composites, aggressive new research is being pursued to define the factors in the cure process that control final material quality. We are using various sensors to establish the state of cure so that on-line monitoring procedures can be developed.

Our state-of-the-art nondestructive inspection laboratory continues to produce new results. We now use our laser to scan a complex shape, automatically teach a robot to follow the correct path with an ultrasonic scanner, and process the image to derive all the necessary information from the data set.

The area of *Materials Design* takes the microstructures developed in the previous areas and predicts the material properties that result. An important effort in this area is to be able to use the behavior model to design new microstructures, in addition to analyzing existing ones. New results are becoming available on electrical properties, structure-property relationships for thermoplastic composites, and viscoelastic behavior, among others.

The research on electrical properties is not only useful for designing and analyzing an end-use product but it also is becoming important for monitoring the orientation state of the fibers. Designers of the future will be able to trade off aspects of electrical performance just as they now do for parameters such as weight and cost.

With thermoplastic composites becoming more attractive for use with advanced fibers, new issues have arisen concerning their processing and properties. Recently, a student completed research on predicting the stiffness of a semicrystalline thermoplastic as a function of its morphology or structure, which is in turn a function of processing conditions.

Another recently completed research effort has produced a thorough characterization of the time-dependent properties of certain short-fiber composites. Recent results on physical aging of materials suggest new approaches for accelerated testing to predict long-term behavior from short-term experiments.

The area of *Mechanics and Design Science* has been a traditionally important one for composites research. It uses the thermoelastic properties from the materials design area to predict the static stess-strain behavior of structures. Again, our strong expertise in this area is producing new knowledge regarding such commercially attractive materials as textile structural composites, using a manufacturing approach that marries the cost productivity of textile manufacturing with the structural efficiency of composites.

Other new research is bringing forth good results on diverse materials, such as ceramic and metal matrix composites. Good cooperation is being achieved with our colleagues at Rutgers in the characterization of ceramic matrix composites.

Our research in the mechanics of composite systems is particularly aggressive in those systems where materials heterogeneity and nonlinear behavior dictate the performance. These systems are becoming more attractive as applications become more demanding.

An important new technique for simplifying the description of complex behavior, called a performance map, has recently been developed. This device is particularly appealing as a design tool for use early in the material selection process.

The area of *Materials Durability* concentrates on end-user concerns by using static deformation behavior to predict long-term performance in service. Its research programs are bearing fruit in fracture toughness characterizations, rate sensitivity, cyclic delamination growth, and wear and erosion behavior.

We are involved in several programs to develop analysis and test methods to characterize the fracture toughness of composites. This is an area of major concern to both the material suppliers and the hardware developers. The loading rate for such tests was recently found to have a significant influence on the results.

Work is continuing in the exploration of the cyclic delamination growth behavior of carbon-epoxy laminates in both peel and shear loading. These data can be used to predict the durability and damage tolerance of structural components.

Computation, Software, and Information Transfer closes the loop from end-user concerns back to manufacturing by developing a software system to allow optimization of any part of the process. Important new results are being obtained in numerical grid generation, flows through irregular domains, three-dimensional image processing, and numerous other areas.

The numerical grid generation work is greatly aided by our connections to the supercomputing facilities at Princeton University and Cray Research, Inc. Good results for irregular domain flows are being obtained through the use of a technique, known as body-fitted coordinates, that eases the set-up of a problem at the expense of computation time.

The image processing work has produced a technique for quantitative characterization of microstructures. The technique uses ultrasonic analysis, adding yet another nondestructive testing tool.

In the past year, we have brought our new VAX 11/785 computer on line, and have begun to expand our communications network so that sponsors can access our software in real time. This mode of technology transfer is growing explosively.

We have made available a dial-up bulletin board, called CCMINFO, to provide self-service information to our research partners. CCMINFO offers research report abstracts, student resumes, electronic mail, a technical meeting calendar, and the CCM library index. We plan to expand this service as much as possible to make the process of technology and information transfer more "transparent" to individual sponsor representatives.

ACADEMIC PROGRAM

Our educational goals are to:

- educate practitioners for industry;
- produce scholars to perform research and development;
- provide Ph.D.s for other university faculties;
- supply continuing education; and
- emphasize "interdisciplinary awareness."

We have a number of interesting and different mechanisms for achieving these goals. To begin with, the Center has a very active undergraduate research program. We begin by identifying the top freshman engineering students at the end of their first year of college. They are offered work in our laboratories for 10 hours a week

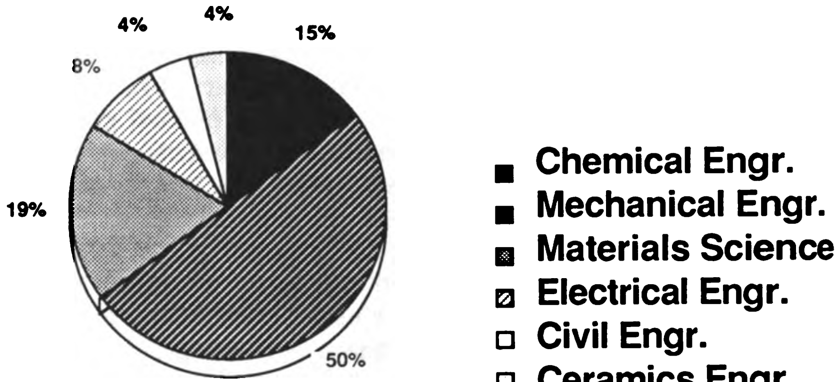


FIGURE 7 The Center draws together 74 graduate students from six disciplines.

during the sophomore year at about $5 per hour. The work typically consists of building and testing composite test coupons. The students are offered full-time lab work during the summer between their sophomore and junior years. The junior year brings another 10-hour-a-week job in the lab. The summer after the junior year is used to give the student additional practical experience by placing him or her with one of the sponsor companies. Finally, the senior year is generally spent in individual research for a senior thesis so that the student can qualify for a degree with distinction. Currently, 40 undergraduates are involved in the program.

The Center has about 74 graduate students working on composites projects. Fifty-eight of them are funded by the Center. The composition of the student population is depicted graphically in Figure 7. Graduate students in the Center are matriculated in traditional departments of the university: chemical, civil, electrical, and mechanical engineering and materials science. Degrees awarded are received through the academic disciplines, rather than through the Center.

Last year, in conjunction with the start of the ERC, some projections were made about the growth of the Center by 1990. In our first year of operation, we have exceeded some of our five-year goals. As shown in Figure 8, we have exceeded our goals for students, met the goal for new courses, and are well on our way to meeting our full-time equivalent faculty goal.

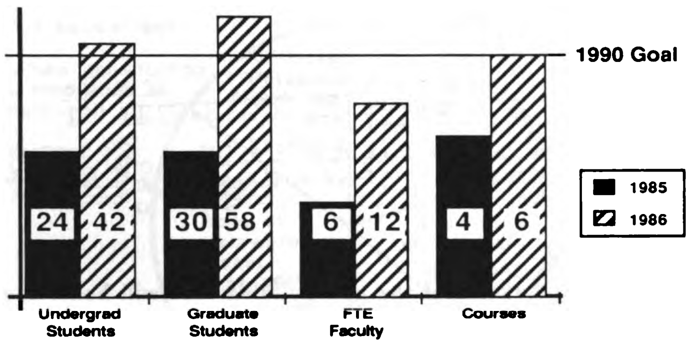


FIGURE 8 Some goals originally set for 1990 have already been met.

In addition to these academic issues, it should be mentioned that we are forming new academic partnerships across campus, such as including the College of Business and Economics in our research on manufacturing cost; with other universities, such as with student and faculty exchanges; and for continuing education, like bringing three professors from abroad to teach in a workshop. In the area of continuing education for interdisciplinary technologies, ERCs will need to play a major role, as they are doing in research.

FACILITIES

In the interest of brevity, I will refrain from listing all the new equipment that has been received or is in the process of being purchased. In fact, we are having to be careful that we schedule deliveries for a time when our new building will be ready to accept them.

The major event in the facilities area during the past year has been the preparation for construction of a new building, which is intended to house the Center for Composites Manufacturing Science and Engineering. An artist's sketch of the new building is shown in Figure 9. About 80 percent of the new building is new construction, with 20 percent being the renovation of Newark Hall. The area of renovation and new construction comprising the Composites Manufacturing Science Laboratory is shown in Figure 10. Our facility fund drive has already succeeded in capturing all of the funds needed to build and furnish the building. The relative contributions of various partners are shown in Figure 11.

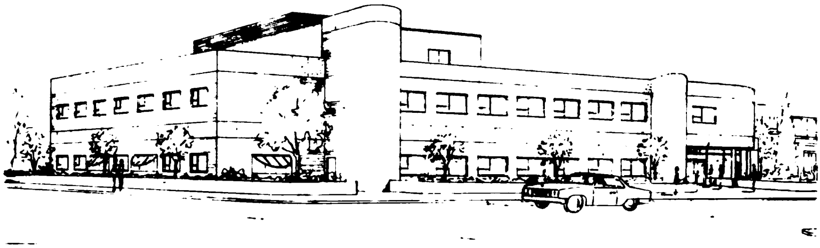


FIGURE 9 Artist's sketch of the new building that will house the composites center.

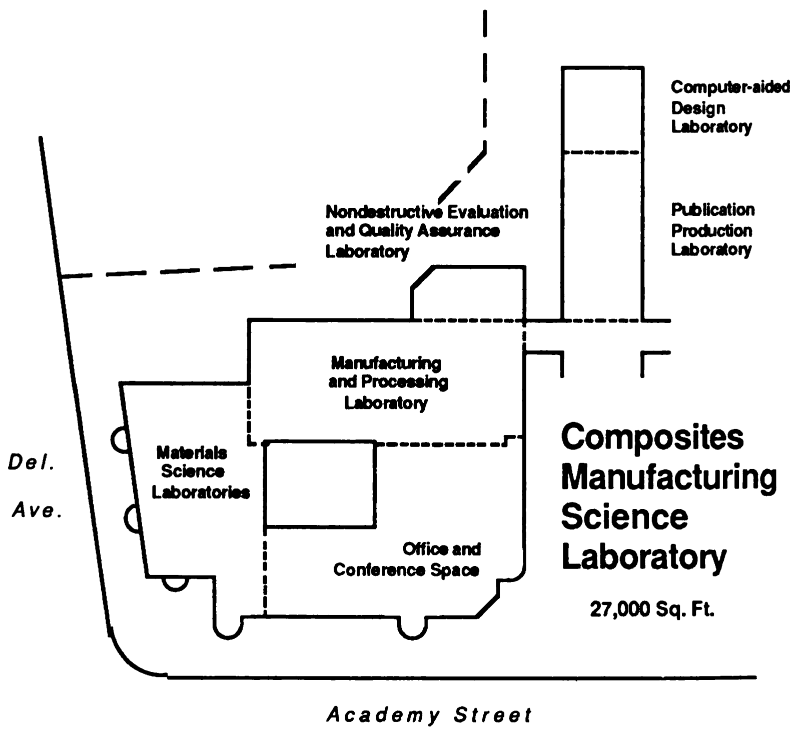


FIGURE 10 Area of renovation and new construction comprising the Composites Manufacturing Science Laboratory.

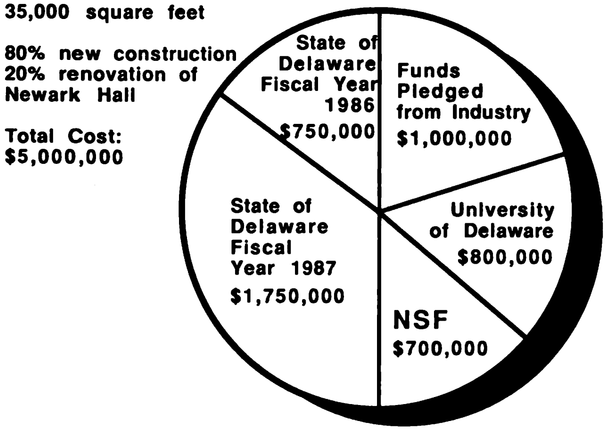


FIGURE 11 Success of facility fund drive.

OPERATING FUNDS

Figure 12 shows the growth of operating funds from the beginning of the CCM. Clearly, the NSF ERC has changed the scope of the program, and it brought the building and army programs as its by-products in spirit, if not in fact. Again, we expect to spend over $5 million per year for the next several years on the composites research that will become ever more important to the renaissance of American manufacturing.

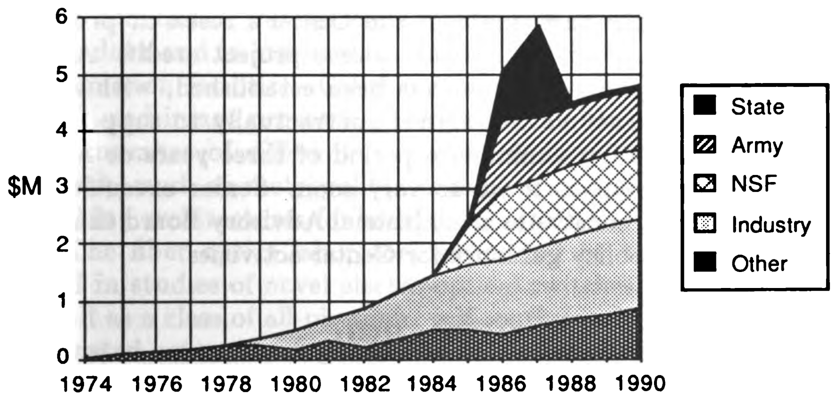


FIGURE 12 NSF funding changed program scope.

Center for Telecommunications Research

MISCHA SCHWARTZ

This is a summary of activities carried out during 1985–1986 by the Columbia University Center for Telecommunications Research, one of the first six Engineering Research Centers established under grants from the National Science Foundation in May 1985.

The Center currently encompasses 20 faculty from four departments in the Columbia School of Engineering and Applied Science, more than 60 graduate research assistants at the doctoral level, and a full-time research and administrative staff of 15. In addition, a large number of master's level and undergraduate engineering students participate in the Center's research program either on a volunteer basis or for course project credit. An Industrial Participants Program has been established, with about 12 companies either having agreed contractually to support the Center activities for a minimum period of three years or having committed themselves to do so very soon. Senior executives of these companies constitute an Industrial Advisory Board that will provide overall policy guidance for Center activities.

RESEARCH

Research activities of the Center focus on integrated communication networks of the future. They cover new system concepts and the technology that is expected to drive these. Participants are organized into four groups: systems and new concepts, very large scale integration architectures for telecommunications, microelectronics and electro-optics, and analysis. Research activities under way range from studies of the basic physics of materials and devices that are expected to play a key role in the integrated telecommunication networks of the future to studies of the networks themselves that will be carrying video, voice, computer data, and other types of communication traffic in an integrated fashion.

As an example, a large group of faculty, students, and full-time research staff has been working on a proprietary integrated local area network called MAGNET. This network uses a ring structure operating at 200 Mbps and has just recently been converted to optical fiber transmission. It currently supports the transmission of interactive data, file transfer, and, to a limited extent, highly compressed digital video. Studies are in progress to find ways of introducing packet voice and higher bandwidth video traffic over this network. A commercial PBX system has recently been installed in the Computer Communications Research Laboratory that houses MAGNET; the plan is to use the PBX system to interface MAGNET with the "outside world," as well as with digital telephones that are installed throughout the facilities of the Center. An expert system that will provide network management and dynamic resource (bandwidth) assignment for users attempting to access MAGNET is under development as well.

Another major project that has just been initiated in the systems area is research into a multimedia, integrated workstation. When completed, this system will integrate voice, video, and computer data and is expected to access MAGNET via optical fiber transmission facilities. Other systems activities include work on speech and image processing, a dynamic multiplexer for integrating a number of different traffic types at an access point of a network, work on metropolitan area networks, and work on novel switching architectures for wide area networks of the future.

The fiber optics laboratory supported by the Center is engaged in studies of novel electro-optical switches and modulators as well as a class of all-photonic, self-routing switches for use with integrated networks. A gallium arsenide laboratory facility is under development in which studies will be undertaken of very high speed electronic devices required for the telecommunication systems of the future. The analysis group is developing a Network Simulation Laboratory to support the analytical and experimental studies of novel network architectures. These represent only a small sample of Center activities currently under way.

An advisory council made up of 15 outstanding engineers and scientists from throughout the United States has been established to provide guidance on the research activities of the Center. This council met with members of the Center Executive Committee in mid-May 1986 to discuss in detail research progress and projects planned for the coming year.

EDUCATION AND INDUSTRIAL INTERACTION

In March 1986, the Center offered a one-week short course on computer communications networks to technical personnel from the industrial participants, as well as to other representatives of industry from throughout the United States. A one-day workshop on telecommunications and operations research, with 200 attendees, was held in October 1985. Two one-day Center research reviews, which were open to all interested individuals as well as representatives of companies and universities interested in the telecommunications area, were held in June 1985 and May 1986. These research reviews will be held annually in May.

In a new experiment designed to encourage industry and university researchers to work closely together, two outstanding research engineers from industry met once a week over a period of a semester with a Center faculty member and five graduate students to work jointly on projects of interest to all. One such group focused on novel metropolitan area network architectures; the other group focused on optical devices for telecommunications. Another researcher from industry offered a special doctoral-level seminar once a week on protocols and distributed processing for telecommunications. To the amazement of everyone involved, 25 students signed up for this seminar—an exceptionally large number for such a course. A regular graduate-level course on packet-switched networks registered 85 students in the fall of 1985, a record number for that course. A new follow-up course in the spring of 1986, on circuit switching and integrated networks, registered 65 students. These numbers attest to the enthusiasm generated among students and staff at Columbia. Notes were written especially for those courses, and a book based on these notes was published in August 1986.*

The enthusiasm and interest generated by the Center was reflected in the large number of visitors, representing universities and companies throughout the world. The number of applicants for the Ph.D. program at Columbia with an emphasis on telecommunications soared to an all-time high. As an example, in the Electrical Engineering Department alone 200 new applications for research assistants were processed, of which only 12 or 13 at most could be accommodated.

As a final point, New York State agreed in mid-April to provide Columbia with a no-interest loan of $42 million to build a high-technology research building. The Center will occupy a substantial portion of that building, which is planned for completion in 1987 or 1990. In the meantime the Center occupies portions of two floors in the Engineering Building, which was made available to the Center and specially renovated by the university.

DISCUSSION

One listener asked whether the very size and success of the ERC at Columbia did not threaten to skew the whole engineering school there toward the interests of the Center and away from the range of other, smaller programs. Dr. Schwartz said that he had not seen or heard any indications that this was happening or that it was a problem. On the contrary, he said that the multidisciplinary nature of the ERC program tends to push vitality outward, into the departments and other related centers on campus, rather than to focus it inward.

---

* *Telecommunications Network*. 1986. Reading, Mass.: Addison-Wesley.

Biotechnology Process Engineering Center

DANIEL I. C. WANG

INTRODUCTION

The Biotechnology Process Engineering Center (BPEC) at the Massachusetts Institute of Technology (MIT) was established on May 1, 1985. In this paper I will present the progress and achievements of the Center over the past year. Since biotechnology is a relatively new industry, a new breed of professionals is needed to solve the cross-disciplinary problems. We intend to create these new professionals through training and education in the biological sciences as well as in engineering principles. The Center also fosters the cross-disciplinary approach to research through its students and faculty. Lastly, a very strong component of this Center is to have active interaction and collaboration with both industry and government.

Composition of the Center

At present the participants in the Center come from five different departments in two schools. Within the School of Engineering the Department of Chemical Engineering has the largest number

This paper was presented at the symposium by Charles L. Cooney.

TABLE 1 Center Personnel (number)

Category	BPEC	Chemical Eng.	Nuclear Eng.	Electrical Eng.	Applied Biological Sciences	Biology	Chemistry	Total
Administration	3	2	0	0	0	0	0	5
Faculty	0	10	1	1	3	3	0	18
Research assistant	0	26	1	1	8	1	0	37
Post-doctoral students	0	2	0	0	2	5	0	9
Research staff	0	1	0	0	4	2	0	7
Support staff	3	3	0	0	1	0	0	7
Undergraduate students[a]	2	30	0	3	1	15	2	53
Visiting (independent and university)	6	0	0	0	0	0	0	6
Total	14	74	2	5	19	26	2	142

[a]Participants in the Undergraduate Research Opportunities Program (UROP).

of faculty participants. As Table 1 shows, 10 professors from the Chemical Engineering Department participate in the activities of the Center. In addition, the Electrical Engineering and Nuclear Engineering Departments each have one faculty member participating in the Center. In the School of Science two departments participate: the Department of Applied Biological Sciences and the Biology Department each have three faculty members. Thus, a total of 18 faculty participants covering a wide range of interests are currently involved in the overall operations and activities of the BPEC. Table 1 also summarizes the origins and total number of all the people that presently participate in the Center. It should be clear that this Center has broad commitments to the various sectors of MIT.

Organization and Management

The overall organization and management plan of the Center is shown schematically in Figure 1. The director of the Center reports to the dean of engineering. A number of separate committees assist in the operation and management of the Center. There is a Policy Committee which consists of the department heads of three departments and the two deans. In addition, there is an Industrial Advisory Board consisting of 11 members from the top management of companies from the biotechnology industry. Lastly, there is an Operating Committee which oversees the education and research of the Center as well as the activities of the Biotechnology Process Engineering Center Industrial Consortium (described below). It is through the Operating Committee that day-to-day management of the Center is achieved. This committee consists of six faculty members from the Biotechnnology Process Engineering Center and three members from industry. The members are selected in such a fashion that various intellectual perspectives are represented. The committee (including the industrial members) meets every two weeks with MIT faculty members, and the full committee (including the members from industry) meets twice a year.

With respect to educational overview, the members of the Operating Committee formulate and identify the types of new courses that will be needed to drive biotechnology education forward in the future. Since research is a strong component of the Center, it is the role of the Operating Committee to review both new and existing

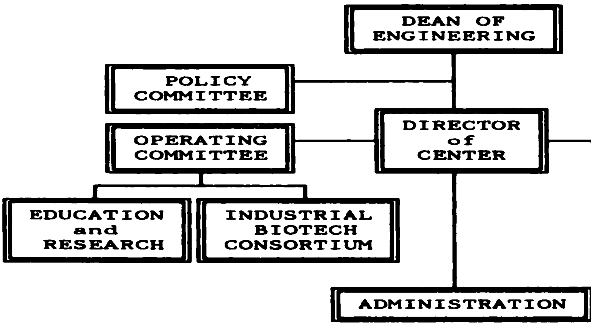


FIGURE 1 **Organisation and management.**

projects. For example, the Operating Committee annually reviews each project in detail and recommends the priority as well as the budget to be allocated among the different projects. In addition, it has the responsibility of coordinating with other members of the Center to identify new research initiatives as well as new participants within the MIT community or elsewhere. The Operating Committee also plays a vital role with respect to industrial involvement and collaboration. It was through this committee that the Biotechnology Process Engineering Center Industrial Consortium was planned, initiated, and executed. The Operating Committee also identifies potential areas of collaboration between industry and Center researchers. Finally, the committee has played a significant role in the planning and execution of various symposia and workshops that were presented to industry by the Center.

EDUCATIONAL PROGRAMS

We believe that the educational program must be a major component of the overall activities of the Center. More specifically, it is our goal to have an educational program in biotechnology process engineering at the undergraduate and graduate levels as well as to provide educational programs to industrial and postdoctoral associates. This section summarizes the various achievements and activities in the past year.

Undergraduate Education

At the undergraduate level the role of education is fulfilled by the Department of Chemical Engineering. We believe that all students interested in biotechnology must have a solid grounding in the fundamentals of chemical engineering. However, elective courses in biotechnology are available to complement the training of these students. At present, four chemical engineering courses serve as electives for those students interested in biotechnology. Some fraction of the course content of these undergraduate courses deals with biotechnology process engineering. It might be noted that a total of 116 undergraduates were enrolled in these four courses. We might also point out some of our plans for the immediate future. For example, two interdisciplinary courses in biochemical processes and biotechnology have been initiated as a result of the establishment of this Center. One of these courses was offered in the spring of 1986 by two departments: Chemical Engineering and Applied Biological Sciences. In 1987 a second interdisciplinary course will be offered jointly by three departments: Biology, Applied Biological Sciences, and Chemical Engineering.

Lastly, at MIT we have a unique program known as the Undergraduate Research Opportunity Program (UROP). This program enables undergraduates to perform research in various disciplines throughout their educational careers. Under the Biotechnology Process Engineering Center we have established quite an elaborate UROP program. Five departments have undergraduates doing research associated with the Center. They are Applied Biological Sciences (1 student), Biology (13 students), Chemistry (2 students), Chemical Engineering (27 students), and Electrical Engineering (3 students). It is interesting to note that this UROP program also offers an opportunity for those undergraduates who have double majors. We currently have five students with double majors in either chemical engineering and biology or electrical engineering and biology. Finally, freshmen are also able to participate in this UROP program. Altogether, in the past year this Center has had 53 undergraduates participating under the UROP program. It is through this type of program that we feel undergraduates are introduced to the principles of biotechnology that they will one day need in graduate studies or in industry.

Graduate Education

At the graduate level, educational programs dealing with biotechnology process engineering are presently found in two departments. Here again, the department primarily responsible for graduate training is the Department of Chemical Engineering. The graduate students obtain their fundamental core training in chemical engineering but have the opportunity to take electives in biotechnology. Because of the Center we now have seven courses at the graduate level in chemical engineering that deal with biotechnology and biochemical engineering principles. In the second year of our program, we plan to have two new courses that will be taught in an interdisciplinary fashion at the graduate level. In the first year, a total of 164 students were enrolled in the elective biotechnology courses offered to chemical engineering students. A second graduate educational program is the biochemical engineering degree program offered by the Department of Applied Biological Sciences. This is an interdisciplinary program administered by three departments. At present there are 35 graduate candidates pursuing the M.S. or Ph.D. degrees. Lastly, we have initiated an Interdepartmental Biotechnology Program, which will be a joint degree program within four departments at MIT: Applied Biological Sciences, Biology, Chemistry, and Chemical Engineering. It is our goal to have a Ph.D. program that will offer interdepartmental and interdisciplinary education in biotechnology. To obtain the financial support for this program we have prepared and submitted a fellowship funding proposal to the Office of Naval Research.

Industrial Education

Industrial education is also a very important role served by this Center. To provide the industrial sector with training relating to biotechnology processes, a number of different avenues have been pursued. For example, we offer special one-week summer courses which serve as continuing education for personnel in industry. Four such courses have been presented, including one called "Fermentation Technology" which had a total of 127 attendees in 1985. Three other summer programs courses were "Biotechnology; Microbial Principles," "Drug Delivery," and "Developments in Modelling, Simulation and Optimization." Through these different summer programs over 200 attendees from industry have obtained training in biotechnology-related principles. A new course entitled "Downstream Processing" was offered in August 1986. Here again, this course will serve an important need in the area of biotechnology practice that deals with product isolation and purification.

Lastly, this Center offers visiting scientists and engineers the opportunity to spend extended periods of time working in our laboratories. In the past year, four companies have sent their personnel to work in our laboratory for long periods of time (i.e., three months or longer). These visiting scientists and engineers are able to capitalize on the intellectual resources of the Centers as well as our physical facilities. This, we believe, provides a valuable interface with industry as well as an excellent opportunity for continuing education and training.

INDUSTRIAL INVOLVEMENT AND COLLABORATIONS

Involvement and collaboration with industry over the past year has been quite active as a result of this Center. We have had numerous research programs sponsored by industry and funded directly to the various investigators participating in the Center. Under industrial sponsorship, 15 companies have supported 16 projects totaling approximately $1.5 million. These programs often leverage the funds coming from the National Science Foundation to the Center. Therefore, industry is able to benefit in a leveraged fashion from their support of Center research. In addition, industry has donated various pieces of equipment to faculty members in the Center. For example, in the past year eight companies have donated equipment worth nearly $770,000. This is often state-of-the-art, new equipment which has been developed by companies and offered to our Center for research and development purposes. It offers our faculty and students an interactive role in examining and improving the equipment as well as providing state-of-the-art equipment for research in our Center. We also received nearly $2.4 million from industry for the construction of a fermentation and downstream pilot plant. The pilot plant became operational in October 1986. It contains equipment that will handle the biotechnology processes from fermentation to product isolation. The Center also collaborates with industry in other ways in research and education. For example, in the past year we have had the use of industrial equipment and materials in 13 different projects. It should be noted that this form of collaboration often offers researchers in the Center the opportunity to conduct programs with materials that are not available commercially. In addition, lecturers from industry have participated in two courses at MIT. Both of these courses dealt with biochemical process technology and biotechnology process engineering. Also, a number of laboratory courses have conducted projects at industrial sites. Portions of three laboratory courses have had students working with the equipment at industrial sites and industrial personnel have supervised the courses. This interaction has provided an excellent opportunity for our students to see and experience work at an industrial laboratory. Finally, in the past year we have initiated and executed the Biotechnology Process Engineering Center Industrial Consortium, described below.

The BPEC Industrial Consortium

Over the past year the Operating Committee has deliberated as to what methods might be most appropriate for industrial interaction and cooperation. As a result of this deliberation, the Biotechnology Process Engineering Center Industrial Consortium program was established. Figure 2 lists the purposes of the consortium and its present status. The rationale for establishing a consortium for industry is that it would provide a more formal basis for interaction and collaboration. It is through such interaction that we believe the identification of the critical needs of industry will occur. These critical needs include those in research as well as in education. It was intended that the consortium would also provide an excellent opportunity for exchange of ideas between the Center and the biotechnology industry. Furthermore, through this formal setting joint projects with industry and the Center could be defined and formulated for successful execution. Lastly, the industrial consortium members receive information and services relating to the activities and other events in the Center. All members of the consortium pay an annual subscription fee ranging from \$2,000 to \$20,000 per year, depending on the size of the company.

As of October 1, 1986, 36 companies have joined the consortium. They represent the chemical and biochemical sectors, the pharmaceutical industry, and the new biotechnology and biotechnology support industries. In the past year, through this consortium, visiting scientists from three companies have spent considerable time at our Center. In addition, two small workshops to discuss problems of mutual interest as well as future needs have been held in the first year of the consortium's operation. One of the workshops was "Animal Cells: Science and Technology"

Purposes:
- Provide basis for interactions and collaborations
- Identify critical needs of industry (research and education)
- Provide opportunities for idea exchange
- Joint projects (definition and execution)
- Provide information and services to members

Status (as of 1 October 1986)
- 36 companies joined; 10 positive indications
- Visiting scientists (three companies)
- Two workshops: "Animal Cells: Science and Technology" and "Downstream Processing"

FIGURE 2 The BPEC industrial consortium.

and the other was "Downstream Processing." In these workshops, very active and lively discussions resulted that helped the participants to identify and address some of the goals that have been established in the charter of the consortium.

Information/Technology Transfer

The last area that we believe is important is the transfer of technology and dissemination of information to the industrial sector as well as to the scientific and engineering community at large. The Center has accomplished a variety of things in this area during the past year. A Biotechnology Process Engineering Center Industrial Symposium was held in October 1985. The symposium was attended by over 500 people from industry, government, and universities. More than 150 biotechnology companies, representing 85 percent of those present, attended. In addition to the symposium, during the past year the faculty members of the Center held individual discussions with industrial personnel from 52 companies interested in biotechnology. These discussions were usually of one to two days duration. The members of the Center have also presented seminars at industrial sites. During the past year, 17 such on-site seminars were presented, with well over a thousand people in total attendance. Other methods of information dissemination by the members of the Center include papers presented at professional societies (12), as well as publications in professional journals (17) and theses (2) arising from the Center.

From the above, it can be seen that the involvement and the interaction between industry and the Center have been both elaborate and active. We have pursued a number of different approaches to carrying out these interactions, including exchange of personnel, establishment of collaborative research, and presentation of papers at large symposia as well as small mini-symposia and workshops. We plan to continue operating in this way to develop an even more active program to interface with the industrial sector in future years.

RESEARCH PROGRAMS

The research programs in this Center are focused on fundamental principles and concepts. Some of the projects address critical and immediate needs facing the biotechnology industries. Other projects are long-range ones that are directed toward the future of this industry. The main theme shared by all the research endeavors, however, is the problems of manufacturing and productivity.

Research at the BPEC is focused in four generic areas:

- Genetics and molecular biology (4 projects)
- Concepts in bioreactor design and operation (8 projects)
- Downstream processing: product isolation and purification (12 projects)
- Biochemical process systems engineering (5 projects)

Genetics and Molecular Biology

Fundamental discoveries in molecular biology and genetics have resulted in the possibility of manufacturing a variety of new biological products. Applications of these biomaterials will have an impact on the food, pharmaceutical, and chemical industries. However, new knowledge is needed on the molecular biology and genetics involved in biological *production* processes that will lead to low-cost products with the correct biological activity.

The research on genetics and molecular biology addresses four fundamental questions:

- How can the production efficiency of specific proteins be controlled?
- How can cellular translation processes for protein synthesis be improved upon?

- How can the post-translational modifications of proteins be modified and controlled?
- How can genetic approaches be used to control secretion and misfolding of proteins?

There are four projects in this area. Each focuses on a central aspect of one of the four questions. They are:

1. Production of specific proteins by mammalian cells
2. Translation control of poliovirus capsid protein expression
3. Modifications and functions of recombinant-derived proteins in mammalian cells
4. A genetic approach toward controlling secretion, degradation, and misfolding of proteins

Concepts in Bioreactor Design and Operation

Research under this part of the program aims at elucidating the basic biochemistry of energy metabolism in mammalian cell cultures and establishing the working interrelationships between physical and chemical environmental parameters, on the one hand, and cell physiology and productivity, on the other. These generic results are used in the optimal design and operation of reactor schemes for large-scale cultivation of cells and the development of effective control strategies that optimize cell and reactor productivities. The research efforts currently comprise eight projects:

1. Fundamentals of mammalian cell biochemistry, applications to culture monitoring, and control
2. Effect of fluid mechanics on anchorage-dependent animal cells
3. Gas-liquid transport in animal cell bioreactors
4. High-productivity bioreactors for suspension of animal cells
5. Strategies for optimal design and selection of mammalian cell production processes
6. Computer control strategies for high-density fermentations
7. Development of a novel, cross-flow, monolithic bioreactor to support facilitated oxygen transfer in adsorbed mammalian cell cultures

8. Large-scale animal cell reactors

Downstream Processing: Product Isolation and Purification

The research program in downstream processing focuses on the critical need to develop recovery processes for genetically engineered proteins and polypeptides. The program represents an integrated assembly of projects, the main objectives of which are to establish fundamental biochemical and engineering principles for existing separation methods and to develop novel and innovative separation approaches. The areas under investigation include cross-flow filtration, liquid extraction, chromatographic methods, biospecific adsorption, and downstream process integration.

The diversity within our overall approach is explained by our belief that no one process nor series of processes alone can be applied to all present and future systems. Each project, although unique in certain aspects, addresses the main generic problems facing the bioprocess engineer: maximization of product yield and purity, retention of product activity and three-dimensional structure, process efficiency, and process scale-up. There are currently 12 specific projects in this area of research:

1. Cross-flow filtration of cell suspensions
2. Extraction of biopolymers using biphasic aqueous polymer systems
3. Protein recovery using reversed micelles
4. Dynamic chromatography for protein purification
5. High-resolution protein separations
6. Affinity escort size exclusion chromatography
7. Immunoadsorption with monoclonal antibodies for large-scale purification of biological compounds
8. Production and recovery of extracellular and intracellular proteins
9. Integration of downstream processes
10. Integration of bioreactor operations with downstream processing
11. Electrically controlled membrane separations in biotechnology
12. Refolding of recombinant proteins

Biochemical Process Systems Engineering

The use of computer modeling and simulation, systems engineering, and expert systems is being examined to enhance our overall capabilities in the design and analysis of biochemical processes. Five research projects are directed at reaching this goal:

1. Computer-aided modeling of cells
2. Development and design of bioreactor systems for mammalian cell culture
3. A knowledge-based expert learning system for the development of separation sequences for protein recovery and purification
4. Simulation in the analysis and design of complete biochemical processing systems
5. Analysis and design of advanced control structures for biological reactors

DISCUSSION

Dr. Cooney was asked who makes the major decisions about reallocation of the Center's budget. He replied that the Operating Committee decides such matters, in close consultation with the director of the Center.

Part III

INDUSTRIAL INTERACTION AND PERSPECTIVES

Remarks: The ERCs as Laboratory and Model

ERICH BLOCH

The Engineering Research Centers (ERCs) are a critical partnership of government, industry, and academia in our country's effort to stay ahead in the international competition. It is our answer to Japanese industrial targeting. The ERCs are our major opportunity to bring about a collaboration between industry and academia; pursue cross-disciplinary approaches to engineering problems; provide a link between theoretical and experimental approaches to help solve problems that are important to the country; and improve the working relationships and cooperation among practicing engineers, faculties, and students. It is a laboratory—one that will help to introduce students to the synthesis, integration, and management of engineering systems.

Eleven ERCs have been established. The first group of them was described in the previous section, and the new ones will be introduced in Part V. Our results to date from the first six centers provide a basis for real optimism; but I would emphasize the fact that this is a new undertaking, and as such, it will inevitably encounter difficulties and problems. If there are no problems in a program as ambitious as the ERCs, I would be forced to conclude that we are probably taking the wrong approach. Therefore, this section will take a look at both the pros and the cons of Center operation and industrial interaction.

The first six Centers are well established. They include 108 faculty members, 260 graduate students, and about 70 undergraduate students. We are also gratified with the degree of industrial support extended to the ERCs. They received $13 million in industrial support, more than matching the $10 million that the National Science Foundation invested during the first year in these first six Centers. The support and participation involved 141 separate firms, and we look forward to increasing that number.

While we are pleased with the impressive level of monetary support, we look to industry for more than just financial support. ERCs need the guidance and involvement of industry if they are to be successful. We need to build an ERC environment that will promote sharing of problems between academia and industry, that will promote team efforts to enhance research and education, and that will foster the development of experimental capabilities not available to individual investigators through the acquisition of state-of-the-art instrumentation.

Beyond the industrial support for ERCs, I can point to further evidence that the concept is succeeding: The ERC model has generated tremendous interest outside the National Science Foundation and has become a model for many new domestic and international efforts. For instance, it is a model for the science and technology centers that have been promoted by the Office of Science and Technology Policy and the former Presidential Science Advisor, George A. Keyworth II, to involve industry in scientific as well as engineering research. The new Department of Defense University Research Initiative has some of the earmarks of the ERCs. I hope that these centers will also develop into collaborative and cooperative efforts among industry, academia, and the government.

In addition, probably no other program in the Foundation has attracted the attention of foreign governments as much as this one has. Whenever we get visitors from Japan, France, England, Sweden, China, and other countries, they are enthusiastically investigating the ERCs as they consider how better to involve academia and industry together in their own national technological endeavors.

Building Industry Participation in Cross-Disciplinary Research Centers

MICHAEL J. WOZNY

PERSPECTIVE: THE RPI EXPERIENCE

My original intention had been to write a glowing essay on a vision of the future by speculating how the Engineering Research Center (ERC) concept can change the way we do design and manufacturing. However, upon reflection, I rejected the idea because, first, it would be pure speculation and, second, I could not do justice to that broad subject in such a short time.

Instead, I decided to subtitle my paper "Insights on Key Issues, from an Academic Who Has Gone Through the Mill." I hope to provide some useful insights into the emerging university-industry culture, especially in design and manufacturing, by "telling it like it is." Thinking back, that kind of information was exactly what I needed when I established the Center for Interactive Computer Graphics at Rensselaer Polytechnic Institute (RPI) nine years ago. In fact, I immediately visited Prof. Nam Suh at the Massachusetts Institute of Technology to benefit from his experience in running a university research center with strong industry collaboration.

The perspective that I bring to this symposium comes from nine years of very successful interaction with industry through a National Science Foundation (NSF) Industry-University Cooperative Research Center. One needs a long time horizon to fully understand the implications and vicissitudes of industrial collaboration and support. My Center at RPI was weaned away from our five-year NSF seed grant several years ago. To date, we have generated more than 13 times the $1 million that NSF originally invested in the Center. Most of this funding represents industry grants, rather than contracts, giving us freedom to pursue long-range research interests. A total of 55 companies have been involved.

However, 55 companies are not actively supporting our program today. The actual number of industrial sponsors varies, and in some cases support depends on issues beyond our control. That was my first lesson: After five years of continual growth, I lost an industrial sponsor. They said, in effect, "Sorry, Mike, we have to drop out of your program. We like your work, but the current unfavorable economic picture is forcing us to conserve cash. We would like to rejoin your program at a later date." That was quite a shock. What was I supposed to do with the students who had suddenly lost their support? As far as the company was concerned, that was my problem. Although we survived this and many other crises, and the company in question did in fact rejoin the program, that first loss made me acutely aware of the dynamics of industrial research interests and funding cycles. I joined the real world.

My shock in reaction to the above situation resulted from my not having thought through carefully enough what the role of industry should be in a university research environment. I can certainly build buffers into the Center's operation to avoid specific industry-related problems, but the articulation of industry's role is still a fundamental one. Based on my experience with funding cycles, I believe that any large university research center that relies completely on industry funding is basically unstable and may not survive in the long run. If it does survive, it may have to compromise its research objectives.

My survival strategy at RPI is to encourage "balanced mode" faculty research involvement in the Center, in which only half of the total faculty research involvement in the Center is supported by industry. The other half is derived from peer-reviewed, principal investigator-type grants, primarily from the government. Graduate student support and equipment maintenance are derived primarily from industry funds. My long-term goal is to set the limit of industrial funding at 60 percent of the total research funding base.

Although funding is important, the real value of industrial interaction is the exchange of knowledge and experience. I am pleased to see that the primary role of industry in the ERC program is meaningful collaboration in identifying and pursuing research on critical problems related to international competitiveness and that the secondary role is the actual funding of research.

A second lesson I learned relates to administrative support. The graphics center at RPI flourished in the difficult start-up years because of the strong administrative support for university-industry cooperative research fostered by the late RPI President George Low through his commitment to excellence and careful planning and by the then Dean of Engineering George Ansell through his vision and action. These men showed me that strong administrative support is necessary, but not sufficient, to guarantee success. Their administrative shield protected me from diversions and allowed me to remain focused on key goals.

Strong support at the top continues to this day at RPI under the leadership of President Dan Berg. A recent article in *Business Week** stated that corporate funding accounted for 30 percent of RPI's total research expenditures in fiscal year 1985. I thought this number was high, so I investigated further. I was surprised to learn that the corporate funding level for the School of Engineering at RPI was closer to 50 percent! This sustained commitment to industrial involvement for well over a decade will be recognized formally at RPI in the May 1987 dedication of a new $30 million building on campus, called the George M. Low Center for Industrial Innovation—a fitting tribute to the man who saw the potential of industrial partnerships, grasped the initiative, and provided sustained leadership.

Strong administrative involvement and support is essential in the establishment of Centers because all the ramifications of significant industry involvement are not clear. The restructuring of university policies to accommodate large Centers will cause us to reexamine fundamental tenets of the university, such as tenure. No one knows how extensive industrial sponsorship of Centers will affect universities in the long term.

* "Now, R&D is corporate America's answer to Japan Inc." *Business Week*. June 23, 1986.

CROSS-DISCIPLINARY RESEARCH AND SYSTEMS INTEGRATION

I would now like to broaden the discussion to address ERC issues that cut across the field of design and manufacturing. This field is clearly central to our international competitiveness. From an historical perspective, this field was actually the vehicle by which the need for cross-disciplinary research centers was originally articulated.

In the summer of 1983 I was asked by the Committee on Science, Engineering, and Public Policy (COSEPUP),* to chair a panel that would prepare a briefing document for the Office of Science and Technology Policy (OSTP) on research opportunities in computers in design and manufacturing.† This panel was the first COSEPUP study to deal with an engineering subject. Our recommendations focused on the need for a research base to combat international competitiveness, the need to nurture a genuine research community, the importance of cross-disciplinary research, and the need to involve undergraduate students. When I, along with Jim Lardner from Deere and Co., an industrial member of the panel, presented the panel's recommendations to George Keyworth (former presidential science advisor) in October 1983, the synergism was immediate. Keyworth was clearly concerned with the nation's declining posture in international competitiveness and was keenly interested in our proposals. When our spirited one-hour briefing ended, Keyworth felt that more time was needed and invited us to return on a Saturday morning to continue the discussion. Thus, three weeks later James Lardner, George Low (chairman of COSEPUP), and I met with Keyworth, Solomon Buchsbaum (chairman of the OSTP advisory committee), and a room full of officials from various government agencies. The core concept of the ERCs emerged from that meeting, including the strategy to form a committee from the National Academy of Sciences to further develop the concept.

---

* The Committee on Science, Engineering, and Public Policy is a joint committee of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

† Report of the Research Briefing Panel on Computers in Design and Manufacturing. 1984. In *Research Briefings 1983*. Washington, D.C.: National Academy Press.

So now, three years later, I want to reflect on the ERC concept in terms of the underlying industrial drivers that presently impel design and manufacturing.

Drivers of Design and Manufacturing

I will start with a broad conceptual model of productivity in an industrial enterprise. Over the past century we have increased our manufacturing productivity primarily by improving the output of individual functional departments in the factory. Design departments optimized their operations without concern for factory floor planning or machining operations. We have now reached a point of diminishing returns, where further optimization of local departments increases the complexity of the global interaction between departments and actually degrades the overall performance of the enterprise. As a result, the paradigm for achieving productivity has changed dramatically in the past 10 years. It now deals with the integration of a computer-based, enterprise-wide information infrastructure to handle the intra- and interdepartmental interaction and automatically control the traditional materials removal/handling production environment.

As one might expect, this changing paradigm has broadened the scope of design and manufacturing research from specific machines to systems and has encouraged more cross-disciplinary activities. I can cite several examples.

In a division of the Boeing Company, all design data sets are generated and shared completely electronically between design and manufacturing. This group has achieved, in effect, a "paperless environment." As a result, an interesting culture change has emerged: instead of the original three draftsmen, only one draftsman is now needed to support a design engineer. The phenomenon is reminiscent of office automation, in which we find managers composing rough drafts directly into a word processor and having secretaries do the final polishing. Although one may argue that the load on the engineer still has not diminished significantly, it is certainly true that the engineer today has more control over his or her environment and obtains better information in a more timely manner.

The Automation Laboratory at the General Electric (GE) Corporate Research and Development Center is involved in a research project called "Art-to-Part." A goal of this project is to interactively design and automatically plan, produce, and inspect complex parts directly from a common geometric data base based on a very sophisticated solid geometric modeler. Although Art-to-Part is reminiscent of projects undertaken by other companies in the past, this project is exemplary because it is tied to reality, it involves university research, and it is succeeding where others have failed. During a recent demonstration to a group of experienced designers from another large corporation, the GE researchers accepted a challenge to design a difficult part proposed by one of the visiting designers. The prototype part was designed, analyzed, verified, and machined within four hours. The astonished visiting designer remarked that the same process would have taken four months in his company.

Why are Boeing and GE successful in these systems integration efforts while other companies are still having difficulty? As always, one cannot discount strong leadership and management. However, a significant part of the answer lies in research philosophy. Both companies found that the most effective way to advance technology and get it accepted is to create focused, bounded pilot projects aimed at producing demonstrable results. Furthermore, the companies limited the size of the research teams to a number below the threshold of bureaucratic interference. (We all know that large projects generally constrain creativity, because management involvement and desired expectations become unwieldy.) Finally, at key stages of completeness, the research results were transitioned and tested in production or quasiproduction environments to ensure the robustness of the systems concepts and algorithms.

These are good lessons for the ERCs. We must ensure that the research in the ERCs remains focused, and that the ERCs concern themselves with transitionable results. There have been cases in the past where promising research was not carried far enough to be transitionable, so that the field stagnated because expectations were not met.

Consider research in solid geometric modeling. I contend that this field could have progressed much faster and could have had a greater impact on U.S. productivity if it had had available the resources of an ERC back when NSF first began funding research in this area. Solid geometry allows us to specify product design data more completely and provides a high-level basis for automatically controlling the overall process to produce the product.

Solid geometric information is essential if we are to achieve the desired degree of automation in the future. Over the past 15 years, with NSF support, a body of knowledge in solid modeling has started to accumulate. The initial flush of success, however, resulted in a premature euphoria among researchers, who predicted that solid modeling was going to "make waves in automation" in the 1980s and remove major roadblocks from flexible automation. Unfortunately, these promises are far from being fulfilled. Had we understood the true scope of the industrial situation, we would have realized that the research problem is significantly more difficult than it was perceived to be. The real industrial benefit of solids is cross-functional. Consequently, the technology will not leapfrog forward as predicted until the analysis, planning, machining, assembly, and inspection functions all work off the same solid geometry data base.

Engineering research in design and manufacturing is embroiled in a major conflict between the inertia of past practices and the promise of future generic principles. It is clear that ad hoc procedures and reliance on the latest technological tricks are insufficient to bring major progress. We need to identify and research at a fundamental level those cross-disciplinary technological building blocks that enable rapid progress. The identification of underlying research issues is not easy. For example, we continually hear that design/manufacturing data bases are inadequate; but we have not been able to distinguish the true fundamental technological requirements from practice-related causes such as past practices, vendor-induced bottlenecks, lack of standards, or inadequate procedures.

We will get to the core of the real research problems only when faculty who understand research are able to team up with industrial engineers who understand the practical bottlenecks. This ERC objective requires that both parties bring their best people to the table. Unfortunately, that is not happening. I will discuss this issue later.

Enabling Technologies

Next, I would like to explore the research issues associated with two enabling technologies of design and manufacturing, namely, applied geometry and software engineering. I want to illustrate that sustained cross-disciplinary research efforts will be required to overcome existing problems in design and manufacturing. We have already discussed the importance of solid geometry. A basic research issue, however, is the lack of mathematical and computational precision in solid models for automated industrial applications. Complex geometric parts are created from combinations of simpler primitive solids and require extensive surface intersection calculations. In the past, when solid models were used primarily for visualization on a graphic display, numerical approximations sufficed. Today, however, the demand is different. Automation requires that modelers (and other pertinent data) drive the production process directly. Consequently, we need very precise geometric representations of complex, realistic parts. This demand is forcing us to characterize the geometric primitive elements by more complex mathematical formulations such as rational bicubic polynomials. Unfortunately, these representations are fraught with unresolved mathematical problems. One of the problems, mentioned by James Solberg in a paper in this volume (see Part II), is the mathematical characterization of the curves of intersection between two combined primitive elements. The precise curve of intersection of two rational bicubic surfaces in space is a polynomial of degree 324, with something like 17 million coefficients. No one knows how to handle such curves precisely in a computer environment, because they challenge our current paradigms for numerical representation and computation. Therein lies the dilemma. We have stated that one of the basic requirements for achieving a completely automated manufacturing environment, from concept through production, is precise geometric models. However, our current understanding of building complex, precise geometric models is very limited.

Software engineering is another enabling technology which is vital to design and manufacturing, and in which research progress is sadly lacking. The design/manufacturing industry has become increasingly dependent on software over the past 15 years, and is very concerned about protecting this growing investment. Meanwhile, computer suppliers are undergoing major upheavals as they make the transition toward networked engineering workstations—a transition characterized by the rapid introduction, and hence short lifetime, of successively more powerful workstations with better cost/performance ratios. The design/manufacturing industry has also become wary of computer-aided design (CAD)/computer-aided manufacturing (CAM) turnkey suppliers whose latest offerings are not always compatible with those from earlier generations. Finally, with the whole industry becoming computer literate, companies now want to pick and choose the best application packages from the growing software vendor market and integrate them into a system that is custom-tailored to their own internal needs.

In a nutshell, the design/manufacturing industry is looking for an open systems network architecture with standard interfaces to all elements and software present in the network. Workstations (computing platforms) should be totally independent of the network environment, and they should be interchangeable.

Although interface standards are not research topics in themselves, they are part of a larger, productivity-stifling software bottleneck that is an important research issue. Every major CAD/CAM turnkey vendor has been forced to stop production at least once in the past 10 years to restructure and rewrite millions of lines of code. The old data structures, complexity of program organization, cost of maintainability, and old programming paradigms could not be extended to the new generation of design/manufacturing applications. "Major surgery" was the only answer.

We need to find new, flexible environments for organizing, developing, and coding large, sophisticated design and manufacturing application software packages that can be restructured and modified, without having to change the foundations. Software packages in the future will be huge. Even today, start-up companies in software applications rarely enter the marketplace without 1 to 2 million lines of code. We do not have the means to easily conceptualize such sophisticated software packages. We do not have good tools or paradigms for generating well-structured, efficient, reliable, maintainable, and error-free code. The evolving object-oriented programming paradigms and "programmer's apprentice" philosophies are promising but represent only the first small step.

Research in software engineering is essential to the future viability of the design and manufacturing industry. The evolution in the future of custom configurations that integrate software packages from different vendors into a system specifically tailored to meet the needs of a company will drastically change our existing vendor industry. We will see the emergence of a software "development tools" industry and a software "systems integration" industry.

DIFFICULT ISSUES FOR UNIVERSITY RESEARCH CENTERS

Finally, I would like to wrestle with some of the truly sticky issues behind the emerging new culture in university research. We might say that the new culture is already here, because it has caught the imagination of the popular press. The *Business Week* article I cited earlier states that "industry is boosting its funding of academic research to nearly $600 million this year and is rushing to participate in on-campus centers that bring together academic and industrial scientists." The reason for this interest is given: "...companies have rediscovered the critical importance of universities in providing the foundations for new products." Although this article catches the enthusiasm of the emerging culture, many deep issues representing fundamental changes in universities remain unresolved. These issues deal with inertia, perceptions, and diverse goals.

Tenure and Reward

The most important sticky issue is tenure. University tenure decisions are a very serious matter. They are based primarily on evidence of the candidate's potential as a future technical leader in a rapidly changing technical environment. In theory, a favorable decision commits the university to supporting an individual for roughly 40 years—a time span long enough to encompass the birth or death of a technical field. Out of a desire to make the best possible decision, universities have passed their responsibilities to outside technical peers who provide relative perceptions on the candidate's narrow field of expertise. These peers are generally unaware of the long-term goals of the university and tend to reinforce the vague tenure criteria aimed at creating only "chiefs." Industry certainly has a better handle on the promotion/evaluation problem and is more willing to give decision-making responsibility to its leadership.

The university system of rewards clearly works against team participation in research. Thus, we find ourselves in a very precarious position in which faculty are not seriously embracing the team concept. They tend to use centers as "watering holes" during dry periods, to replenish funds for their own independent research. These faculty never really commit themselves to interdisciplinary research, but simply go through the motions.

Part of the problem lies in our definition of problem-focused, cross-disciplinary research. Cross-disciplinary research is very different from development. Cross-disciplinary collaboration in research has been responsible for many of our innovative ideas. We can all recall situations in which two researchers from entirely different backgrounds collaborated to create an entirely new direction for a field. The fresh perspective was just the catalyst needed for substantial progress. In such cases, the collaborators were experts in their own disciplines. We tend to overlook the fact that researchers must be firmly grounded in their own discipline before they can contribute meaningfully to a cross-disciplinary research effort. Thus, an individual must still work on the fundamentals of his or her field, as well as contribute to the cross-disciplinary research effort.

This aspect raises an interesting question. Are we doing our young faculty a disservice by pushing them too quickly into cross-disciplinary efforts? It is easy to recruit new faculty because they generally have no base of established support. However, they must be given time to establish themselves as experts. We need to increase the rewards for doing team research. Does that mean that the Center should take on the responsibility of guiding a faculty? This runs counter to the traditional role of an academic department. It is not clear what role we expect a Center to play.

Conflicting Motivations

The other sticky issue I want to discuss concerns industry's perception of university research relationships. The basic problem is the reconciliation of diverse goals. Like it or not, industry is primarily interested in attracting our top-quality students. Except for corporate foundations, most industry managers are necessarily driven by tangible, near-term results. They view university research programs as extensions of their own laboratories, and expect to measure progress in similar ways. They look for expedient solutions with few diversions. If the problem is long term, they expect minimum-risk approaches with tangible progress at prescribed intervals.

There is nothing wrong with this attitude except that it is one-sided: industry is taking and the university is always giving. Our current dilemma of not having enough American graduate students to fill the open faculty positions is a case in point. Even when good research relations have been established, industry is reluctant to give up strong technical researchers to universities for any length of time. Most industry visitors are sent to universities for education and retraining. Fortunately, the exchange of knowledge and experience has been extremely useful to universities. However, we can only dream about the leaps we could make if the appropriate industrial researchers could participate in research. We need to develop a reward structure that will encourage topflight industry researchers to spend extended periods at universities. Movement in the opposite direction, with key faculty taking sabbaticals in industry, is on the increase and has been well received by both sides.

Stability in Funding

Another aspect of industrial interaction deals with the stability of industrial funding. This is not a new problem, but it has developed a new twist: the significantly higher levels of industrial funding needed for Centers has created a precarious situation for universities in which the tail wags the dog. Center budgets are typically much larger than the uncommitted portion of an academic budget. Consequently, most institutions could not tolerate—either financially or programmatically—a sudden large decrease of industrial funding in a Center. Unfortunately, industry tends to terminate funding on short notice in stringent economic times, without regard to student continuity. The serious erosion of the computer industry in the past year, for example, has compromised promising new programs. Realizing that support for long-range research is most likely to be eliminated first, some university research centers have developed short-term survival strategies, such as job shopping, that may not be in the best long-term interests of the university, of students, or of the nation.

I expect that the ERC program will create a fallout similar to that of other programs in the past. For example, IBM estimates that 50 schools that were not awarded grants in the company's CAD/CAM equipment competition four years ago initiated manufacturing engineering programs anyway, since all of the basic planning was already complete. They found other sources of funding. Similarly, we will see many new ERC-like Centers being established, with and without government funds. All of these Centers, in aggregate, form the backbone of the emerging cross-disciplinary, problem-focused culture. Given that these Centers are important to international competitiveness, I believe that the federal government has a responsibility to ensure their stability through lean economic times. Perhaps a loan program with future industry guarantees could be developed.

Strategies for Success

Barring adverse economic conditions, there are various strategies that encourage long, stable relationships. The most important is the need to identify genuine "champions" on both sides. Centers must work very hard to convince company management that the relationship has value for the company. If no one in the company is willing to champion the cause, then the relationship will eventually dwindle and die. Our lasting industrial relationships at RPI have been those with strong leverage on both sides.

The second most important strategy is to define research efforts in terms of bounded cases with demonstrable milestones. Industry understands tangible results that are delivered at some mutually acceptable deadline, whether it is one or two years in the future. Although papers can and do suffice, a demonstrable engineering prototype of an innovative concept is worth its weight in gold.

As Nam Suh mentioned in his paper (Part II, this volume), the ERCs represent the vanguard of a new dimension in university research—namely, attacking cross-disciplinary problems of national importance by working cooperatively with industry and then translating this experience to undergraduate students. The ERC program represents the integration of bold new ideas with the best experience gained from other grant programs, such as the NSF Industry-University Cooperative Research Center Program and the IBM CAD/CAM equipment program. All these programs have had an important impact on industry-university interactions. The ERCs represent a major step in securing our research base. We must diligently protect this base against cries for "quick fixes." We must carefully balance essential near-term efforts without jeopardizing our long-term goals for a stronger fundamental base. At the same time, we must be realistic in our expectations. The time line for practical realization of significant innovative research results is much longer than the five-year initial phase of the ERC program. For comparison, Ivan Sutherland's Ph.D. research on "Sketchpad," which is among the most innovative American ideas of the last 25 years, incubated for 12 years before exploding into the computer graphics and CAD/CAM industry we know today.

The ERCs are well-positioned to make significant contributions to international competitiveness in the long term. I am reminded of the observation an Australian colleague once made about the American way of doing things. He said that we are very crisis-oriented. We wait until the situation gets out of hand before we bring everything to bear on solving the problem. Once it has been solved, we forget that the problem ever existed. We have a serious international competitiveness situation in front of us today. I am confident that, through initiatives, such as the ERC program, we will resolve this crisis as we have resolved others before it.

DISCUSSION

An observation was made from the floor that the ERCs seem to place greater emphasis on people coming in from industry than on people going out from the university to interact with industry. Dr. Wozny responded that that is the natural direction of flow when a Center is just getting established. Once the faculty understand the industry culture—what its needs are, how industry does research—and have established a strong relationship, then the faculty tend to go more confidently into industry. One aspect of the relationship, according to Dr. Wozny, is that the Center must set goals that industry understands and must be able to present its achievements in a clear, demonstrable fashion. One listener observed that, with various centers and institutions deriving much of their support from industry, there will be a limit to the total industry capacity for support. Dr. Wozny agreed, and suggested that for this reason it will be important for NSF to see that the ERCs are fairly evenly spread across potential supporting industries. Finally, to a question regarding the pitfalls of interdisciplinary research for younger faculty, he said that he counsels them to become well established with their departmentally oriented tenure and review groups before identifying too closely with the Center.

Stimulating Innovation: Problems and Opportunities in an ERC Environment

ALAN S. MICHAELS

THE ENVIRONMENT FOR INNOVATION

Constructive application of scientific and engineering knowledge to the development of novel and useful solutions to important social needs is the essence of innovation in our modern technological society. An understanding of the factors contributing to innovation, and of the means for creating an innovation-conducive environment, is central to the maintenance of the nation's global stature in technology, and is thus a vital concern of government, industry, and academia in today's highly competitive climate.

Early in the industrial revolution, the most significant innovations were the creations of dedicated individuals with limited scientific training but with a keen awareness of need and opportunity; moreover, in those times the physical and financial resources required to demonstrate feasibility of an innovative concept and reduce it to practice were modest. Thus, the major inventions of the nineteenth and early twentieth centuries—and the innovators responsible for them—are legends and role models of our time. While today the possibility of such important individual innovations—I call them "eureka inventions"—cannot be excluded, the probability that they will occur has largely evaporated. There are three reasons for this: First, the important problems in need of innovative solution today are often so complex, and so difficult to define, that few individuals have the breadth of knowledge needed even to identify the need precisely, let alone conjure up rational means for satisfying it. Second, imaginative solutions to complex technical problems appear increasingly to originate at the interfaces between traditional scientific and engineering disciplines, where constructive interaction between individuals with differing perspectives and viewpoints is essential. Third, the time, experimental sophistication, and expense required today to demonstrate practical utility of an innovative concept is so great that only large, well-funded teams of specialists equipped with elaborate facilities are usually qualified to perform such a task.

These considerations prompt me to propose the key elements of—and the ideal environment for—innovation in today's world:

1. need-awareness;
2. interdisciplinary team effort;
3. team leadership that can define the need clearly and encourage participative project management with specific goals;
4. adequate physical and financial resources to test alternative solutions and prove feasibility.

In our society, the first beneficiary of technological innovation is usually industry, since innovation generates revenue, profit, and competitive advantage. Such benefits are highly visible, quickly realizable, and easily quantified. Thus, it should be no surprise that U.S. industry has been the cradle of innovation in this century. While industry's motivation to innovate may be obvious, its ability to provide an environment that is uniquely supportive of the innovation process has not been impeccable. In my experience, a favorable environment will be created in an industrial research and development (R&D) organization only if the following special conditions exist:

1. the organization is staffed by individuals representing all or most of the scientific and engineering disciplines relevant to the broad corporate mission;
2. all disciplines are regarded as being equally important to achievement of the group's goals; and
3. the group's activities are channeled into "problem-focused" projects, wherein interdisciplinary teams managed by goal-oriented leaders address specific needs and well-defined objectives.

Such conditions are most often encountered in relatively small R&D organizations within young, high-technology ventures managed by intuitive, dynamic founder/entrepreneurs. The absence of rigid hierarchies, awareness of the corporate mission at all levels, acceptance of the founder/entrepreneur as a role model, and group preoccupation with corporate survival all facilitate the creation of this innovation-stimulating environment.

In larger, well-established corporations, R&D organizations tend to be structured along standardized disciplinary lines, with the greatest visibility and influence being accorded to those scientific and engineering specialties with historical records of corporate accomplishment. Management responsibility in such organizations usually devolves on those who are past performers; and communication among the R&D leadership, corporate planners, and top corporate management is, all too often, poor. If the company (or industry) is in transition due to advancing technology or changing market forces, its stereotyped R&D organization may well be unresponsive to emerging corporate needs and unable to perform its innovative function. Such organizations can hardly be happy homes or effective training grounds for bright and creative scientists and engineers. Companies or industries beset with these problems are unlikely to survive long in today's climate of rapid technological change.

ERCS: A RESPONSE TO THE CHALLENGE

America's complacency about its ability to exploit scientific discoveries rapidly and reduce them to practice for society's benefit—and thereby to maintain its competitive dominance in the world economy—has been brought under critical scrutiny due to the rapid ascendancy of countries in Europe and Asia in the international markets for high-technology products and services. Responsible leaders in both the public and private sectors of our society are now aware that, for the United States to maintain its stature in the international trading community, it must marshal its intellectual and economic resources to provide the *training* and *motivation* required for present and future generations of young scientists and engineers to transform modern scientific and engineering discovery into useful industrial practice. The traditional forum for *training* has been the university; the vehicle for *motivation* has been industry.

The establishment of the Engineering Research Centers (ERCs) program by the National Science Foundation (NSF) recognizes the importance of both need-focused research and cross-disciplinary collaboration in the successful reduction to practice of scientific discovery, and acknowledges the desirability of providing such training and perspective in the university. While surely commendable in its objectives, in my opinion the program faces some formidable problems in its execution.

Potential Problems

One potential problem relates to the suitability of the university environment for cross-disciplinary collaboration. Another concerns the attitudes that prevail within the university toward problem-focused research. The third relates to the climate within the university for innovative R&D. If it is to be successful, the program must engender some major cultural accommodations within the university, and must forge inter-relationships among industry, academia, and government unlike any in existence today.

To begin with, the concept of cross-disciplinary collaboration is incompatible with the principles of scholarly pursuit in academia. Distinction on university faculties is achieved through individual research accomplishment, not group effort. Coauthorship (other than with one's students) is regarded as a sign of intellectual inferiority. Collaboration with colleagues—particularly with those in other disciplines—is usually regarded as a sign of incompetence or disloyalty. There are simply no incentives or rewards provided in the academic environment (to either faculty or students) for interdisciplinary research or instruction.

Second, the principal goal of academic research—be it in natural science or in engineering—is *discovery*. Discovery means finding new phenomena, or developing new theories for explaining or predicting phenomena. This goal is inconsistent with that of applying knowledge to meet a societal or industrial need. The latter is considered by most academics to be *development*, and thus intellectually inferior to *research*. Faculty who engage in development are often denigrated by their more "academically pure" colleagues, and may be accused of pandering to industry for recognition and support.

Lastly, the prospects for technological innovation within the university are further hobbled by the general lack of awareness among faculty of the *real* needs of society, and by the absence of the entrepreneurial leadership which drives the creative process. Thus, the university environment lacks the management skills that, in the industrial R&D setting, are essential to stimulating innovation.

Possible Solutions

By providing seed funding for need-oriented Engineering Research Centers within our universities, NSF has taken an important step in providing an incentive for cross-disciplinary, problem-focused, collaborative research and training within our educational system. Also, by seeking industrial participation in the oversight and support of these Centers, it is providing the additional incentive for testing the relevance of Center-sponsored research to real societal needs. But these steps alone will not be sufficient to ensure that the objectives of the ERC program will be achieved.

Science and engineering faculties have, with many years of experience in dealing with federal funding agencies, become very adept at structuring research proposals responsive to the sponsoring agency's guidelines, but which in execution are often diverted to their own private research interests. The practice goes under the genteel title of "grantsmanship." Much vigilance will be needed to ensure that cross-disciplinary programs conceived in response to ERC solicitations retain their identity after the Center is established, and that codirection of such programs by the specified faculty members is maintained. This will impose upon NSF and upon the ERC's oversight committees an obligation to monitor ongoing programs and to frequently assess and evaluate program progress and accomplishments.

It is also my view that successful initiation and continuation of interdisciplinary programs in an ERC framework will require special support from university faculties and administrators in the form of new incentives for participation in such activities by students and faculty. These might include (1) special awards and citations for important contributions to such programs; (2) special credit toward promotion and tenure for faculty engaged in such activities; (3) creation of new openings within engineering department faculties to be filled specifically by scientists or engineers representing complementary disciplines; and (4) broadening of the requirements for advanced degree awards in a given engineering discipline to include formal training in another discipline. Only with such incentives in place will students and faculty alike regard the ERC as a suitable milieu for education and professional development.

Assurance that ERC programs will be genuinely need-oriented and problem-focused will, in my opinion, require input and guidance from industrial technical and business leaders whose judgment about the practical values and "commercializability" of research results is surely different from—and probably better than—that of engineering and science faculty. Companies with expressed interest in the mission of a particular proposed Center should be solicited (by the university or NSF) to contribute the services of their research and corporate planning managers for collaboration with Center faculty in the structuring of Center projects and the establishment of Center research priorities. Projects that fail to receive support or sanction by industry should probably not be eligible for NSF funding. This participation of industrial management in specific research program appraisal should not only be sought in evaluating the merits of proposals for new ERCs but should also be sustained in every established Center for evaluation of both new and ongoing research projects.

Probably the greatest obstacle to be surmounted in the ERC environment is the creation of a climate for innovation, which, as I have noted previously, is a unique feature of the entrepreneurially motivated industrial R&D organization. One approach—admittedly a radical one—to achieving this end would be to persuade one or more companies participating in the Center to assign to a specific project of particular importance to that company one of the company's most qualified research managers to serve as project leader, and to have this individual take up residence at the university in that capacity for a period of a year or more. Each such project leader would be accorded visiting faculty status during his or her residence and would have full responsibility and accountability for the project under his or her direction. Full-time faculty members associated with that project would perform their customary advisory/supervisory functions and would, of course, have final authority for granting of degrees and publication of research results. In this manner, students and faculty alike would have the opportunity to participate in research managed in part with industry's perspective, and industrial research managers would benefit from the intellectual diversity and fresh point of view of the university.

Extracting this level of commitment and participation by industry in the ERC program will be a formidable task. It will necessitate the creation of a special array of incentives to industry (requiring important concessions by both the federal government and academia) in order to make the ERC-industry liaison both economically and professionally appealing. Inasmuch as the outfall from an ERC's research should be novel and commercializable products and processes, it should be the responsibility of the Center and university to protect the developed technology via the international patent system, and to facilitate speedy transfer of the technology to the industrial sector for commercialization. Licensing of Center-generated proprietary technology to industry should be negotiated on terms that ensure a reasonable royalty return to the Center. The funds so received should be used in the following ways: first, to reduce Center operating costs (and thus the burden of federal or industry support); second, to reimburse industry and the federal government for prior contributions to Center support; and third, to support otherwise unfunded university research. (I personally am strongly opposed to monetary compensation to individuals for inventions, whether in industry or academia, in view of the invidiousness and rancor it engenders.)

It is also my view that companies that participate in or contribute to a Center should be given first consideration and preferential treatment with respect to licensing of Center-generated technology. Wherever possible, participating companies should be granted options to exclusive or limited-exclusive rights, or to nonexclusive rights on more favorable terms than are extended to nonparticipants. In order to retain such rights, licensed companies should be obliged to demonstrate due diligence in carrying out prompt development and commercial practice of the inventions. (Such arrangements may necessitate enactment of new federal legislation to protect the participants from liability for violation of existing antitrust statutes—a position which I feel NSF and the National Academies should energetically support.)

Particularly favorable consideration should, I believe, be accorded those companies that provide research managerial personnel for assignment to Center-originated projects; an appropriate covenant would be to grant such a company an option on an *exclusive* license (bearing royalties to the Center) to any and all inventions evolving from the project to which its research manager was assigned. This arrangement might well stimulate the participation in the Centers of quite small, entrepreneurial companies with limited financial resources that would normally regard an association with a Center as an unjustifiable extravagance.

CONCLUSION

It is clear that, if the Engineering Research Centers are to become the future breeding grounds for creative, problem-focused engineers, as well as the training ground for innovative, need-oriented, cross-disciplinary research, they will require imaginative, participative management and direction by industry, government, and academia. Creation of a suitable environment for such collaboration will require some agonizing cultural readjustments by all three institutions. It should be worth the effort: The fruit of success may be the survival of America as a global power and center of influence in the next century; its failure could spell a dismal future for us all.

DISCUSSION

Discussion here centered on the suitability of the university environment for fostering cross-disciplinary research. It was pointed out that radar, modern electronics, computers, and biotechnology are all examples of successful university-based cross-disciplinary collaboration. The similarity between World War II and the current economic situation as drivers of such activity was noted. One member of the audience said that the cultural capacity to adapt to today's challenges varies greatly across the nation's universities, and that the ERCs are being placed in those that are most able to adapt. There was further discussion as to how much the ERCs are or should be problem-driven. One Center director disagreed that they are essentially problem-driven, saying that they are and must be oriented primarily toward fundamental work. Dr. Michaels responded that any ERC research ought to be identified with a demonstrable societal need in order to be justified as a Center activity. The issue of "industry subcontracting"-type problems led to a suggestion that ERCs could evolve into research institutes like Battelle Memorial Institute. Dr. Michaels rejected this notion on the grounds that the educational function would be lost.

Highlights of the Interaction with Industry: The Engineering Research Center for Intelligent Manufacturing Systems

JAMES J. SOLBERG

The research and educational aspects of the Purdue Engineering Research Center (ERC) were described in another paper in this volume (see J. J. Solberg, "Engineering Research Centers for Intelligent Manufacturing Systems," Part II). Finding methods for more rapid and effective technology transfer is an equally important part of our mission. Successful technology transfer involves far more than the teaching of students and the publication of research results. It requires a direct relationship between the partners that extends over periods of months or years. Furthermore, it must be understood that the flow goes in both directions. That is, the academic side has as much to gain in the exchange as does the industrial side.

Companies are able to participate formally in the Center's activities through two principal avenues. Major contributors are called *partners*, or CIDMAC members. (The acronym stands for Computer Integrated Design, Manufacturing, and Automation Center. This Center predates the ERC, but continues as a joint sponsor with the National Science Foundation [NSF] of the ERC work.) These companies have representation on the Policy Advisory Committee and the Technical Advisory Committee, and help to guide the direction of the Center. In addition, they may have on campus a full-time representative of their company (a site representative), whose job it is to provide a day-to-day interface between the company and university communities. Thus, the member companies are participants in the true sense of active involvement. There is a reasonable limit to the number of companies that could participate in this manner—probably in the range of 12 to 15. At the time of this writing, there are seven partner companies. They are:

Alcoa
Chrysler Corporation
Control Data Corporation
Cincinnati Milacron
Cummins Engine
Ransburg
TRW

The other form of participation in the ERC is as an *affiliate*. An annual fee of $25,000 entitles affiliate companies to receive a variety of benefits, including a newsletter and reports, and to attend several meetings held throughout the year. There are now nine official affiliates; eventually we expect the affiliates to number perhaps as many as 30 to 40. Committed affiliates are:

Borg Warner
CIMLINC
Hughes Aircraft
Delco Remy
Honeywell
Kodak
Navistar
Symbolics
Timken

Several other companies are close to commitment but did not complete the agreement in time for this publication.

It is understood that the members serve as representatives of American industry at large, not just their own interests. Although the companies who join us may enjoy special advantages by virtue of their close involvement in the work as it occurs, the Center does not restrict dissemination of results. Indeed, it is the explicit intent of the ERC to disseminate our results agressively, so as to enhance the competitiveness of as much of American industry as we can reach.

The benefits offered to the companies that participate either as partners or affiliates include:

- an annual meeting,
- an annual report,
- a newsletter,
- a research bulletin,
- technical reports,
- technical update sessions,
- a log-in to an electronic data base, and
- visits and tours.

Of these, some are available to the public (in some cases for a separate fee); but the annual meeting, log-in, and technical update sessions are for members only. The partners have the same privileges as affiliates, plus the opportunity for more direct and immediate involvement through a site representative and a representative on the Policy Advisory Committee.

The ERC publishes a newsletter and a research bulletin. The former is distributed broadly, as a pure news document. The latter is reserved for members and contains potentially valuable advance information about the research that is under way. Eventually, of course, all the work is made public through the standard process of academic publication.

Another forum for industrial interaction is a series of "update" sessions, held three or four times throughout the year on varying technical topics. Attendance is limited to partners and affiliates. The first was held on June 17, 1986, on the subject of industrial robotics. At the end of the session, an evaluation was conducted to determine how the format might be improved. Those present were enthusiastic about the possibilities that such a meeting offered and made a number of suggestions to enhance the interchange.

We have established an electronic mail link to each of our participating companies; it is rapidly becoming the principal medium of communications (replacing both the telephone and paper mail). In the future, we plan to expand this capability by creating an electronic data base that our member companies can access remotely to get up-to-date information about any of the active research projects. Eventually this system will provide a convenient way to search for some piece of information or to locate the right person to whom an inquiry should be addressed.

It is worth pointing out some of the intangible benefits (to both sides) that are derived from the close interaction of the university and industry. These may, in fact, outweigh all of the more concrete benefits. Most importantly, the influence of industry in the planning of research and educational activities ensures that the long-term thrust of the ERC will in fact address the true needs of industry. The stimulation in the opposite direction ensures that the companies are thinking of the possibilities for use of future research results and the proper use of the human resources that we create. Several of our partner companies have credited their involvement in our Center with helping them to recognize opportunities that would otherwise go unnoticed.

The selection of Purdue as an ERC site provided a kind of visibility that we had not fully anticipated. We have received a large number of visitors who have come to Purdue specifically to find out about the ERC work. For example, in the month of April alone, 389 people toured the Purdue ERC laboratories. Although this traffic represents a substantial burden, we are pleased to have the opportunity to "spread the word" to very receptive listeners. This, too, is part of the educational responsibility of the ERC.

Highlights of the Interaction with Industry: The Center for Composites Manufacturing Science and Engineering

WILLIAM A. DICK

BACKGROUND

The Center for Composites Manufacturing Science and Engineering was established by the National Science Foundation (NSF) in May 1985 to address the barrier problems in the efficient utilization of composite materials in industrial, commercial, and military applications. This paper describes the partnership of university, business, and government that is required to fulfill a broad spectrum of educational, research, and technology transfer goals. In particular, it examines several unique mechanisms developed at the University of Delaware for actively working with industry for the mutual benefit of all partners.

The development of new stiff, strong, and lightweight materials systems consisting of high-performance fibers unified by advanced binders—composite materials—has played a key role in the success of the space program as well as in the development of new military systems. Today, while such materials continue to be important in these areas, significantly broader technological and economic roles are emerging for composites to meet crucial national needs in the commercial sector. It has become evident that these materials have the potential to revolutionize the technologies associated with the commercial aircraft industry, ground transportation, consumer products, and industrial machinery.

Industrial Interaction History

Center for Composites Manufacturing Science and Engineering

1974 Center for Composite Materials Founded

1978 University/Industry Research Program Established

1985 NSF/ERC Center Founded
- Delaware/Rutgers Connection Established

1985 Composites Manufacturing Science Laboratory Initiated

1987 New Composites Center Building to be Occupied

FIGURE 1 The Center for Composites Manufacturing Science and Engineering: milestones in the interaction with industry.

To this end, a center for composite materials was founded at the University of Delaware in 1974 to examine the fundamental behavior of composite materials. Figure 1 depicts the principal organizational milestones in the Center's history, which were described earlier in this volume by D. J. Wilkins (see "Center for Composites Manufacturing Science and Engineering," Part I). A unique university-industry research program, Application of Composite Materials to Industrial Products, was initiated in 1978 to bring additional resources to the university and, more importantly, to provide real-world engineering problems for graduate research topics. Recognizing the composite materials industry as one of critical national importance, NSF located an Engineering Research Center (ERC) at Delaware in May 1985. At that time, a connection was formed between the University of Delaware and Rutgers University to address issues surrounding ceramic matrix composites. The new Composites Manufacturing Science Laboratory program began in September 1985, incorporating manufacturing equipment and facilities supported by industrial gifts.

The Delaware-Rutgers-Industry-NSF program has been developed to accelerate the acceptance and utilization of composite materials technology. Industry provides financial and technical

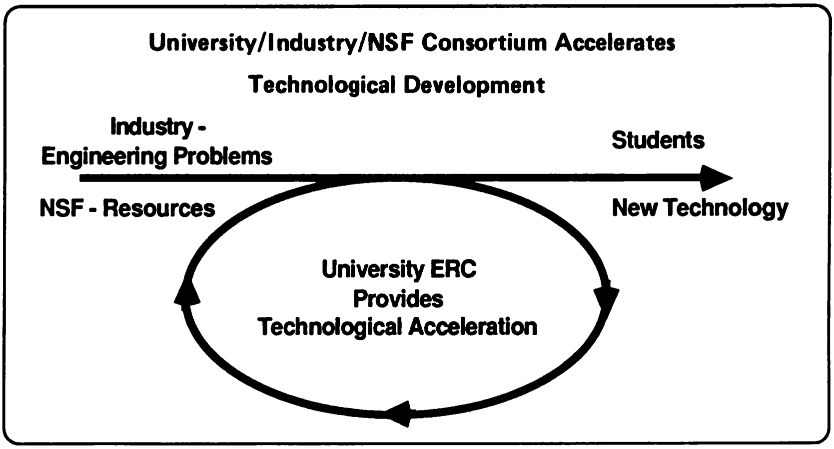


FIGURE 2 ERC program accelerates technology.

materials technology. Industry provides financial and technical resources, while it also contributes barrier engineering problems for study. NSF provides financial support and a fertile environment for attracting additional industrial participants. The universities, through the ERC program, provide the discipline synergism necessary for technological acceleration, producing both new technology and well-educated and trained students for work in the field (see Figure 2).

INDUSTRIAL INTERACTION

The key to a successful industrial program is interaction. Today, schools of engineering are unable to advance technology unilaterally. Universities are very able to attack engineering problems when they are uncovered, but the academic world has no inherent engineering problems to address. Rather, the scientific and technological problems of interest to engineering students are the barrier problems in the industrial work place.

The university-industry research program established at the Center for Composites Manufacturing Science and Engineering has been very successful. The program was initiated in 1978 with six companies representing material suppliers and automotive manufacturers. The consortium program has grown to 35 corporations, including the premier fiber and matrix material suppliers, automotive and aerospace companies, and general commercial industries. Current sponsor companies were identified in Figure 5 of D. J. Wilkins's paper (this volume).

Every opportunity to interact with the industrial community is taken to provide direction toward problems worthy of consideration. Current and potential industrial sponsors visit the Center on a regular basis. An average of more than two companies visit the university each week. Each visit includes an overview of the Center program, current highlights of progress, a technical presentation of particular interest to the visitors, and a laboratory tour. Often, individual meetings with faculty and research staff members are also arranged.

Very important to the success of the ERC is that each visiting group is requested to present the current work ongoing at their organization as well. Our experience has been that we could not have *paid* these industrial visitors for the information that they share with us. However, they are willing to discuss their barrier problems with us because otherwise we would be unable to understand the problems they want us to solve.

International Companies

The companies participating in our program are many of the most important players in their field; they represent not only a spectrum of industries but also a variety of nationalities. International corporations are pervasive in the modern economic world. The largest computer company in the world, International Business Machines Corporation, proudly proclaims itself to be an international corporation. Shell Oil Company, an American household word, is a wholly owned subsidiary of Royal Dutch Shell.

Furthermore, international technology is important. In the composites field alone, the technology for manufacturing carbon fiber was invented independently in the United Kingdom and Japan. Current American technology for fiber manufacture is licensed from the Japanese. Major innovations in the computer-aided engineering and design of structures are emerging in Europe, particularly in France and the United Kingdom.

New technologies continue to develop in a rapidly changing marketplace. A policy has developed in the Center for Composites Manufacturing Science and Engineering whereby *any* company may join the consortium provided that the information flow is two-way. This policy has been well accepted by all our sponsors, both domestic and foreign. We believe that it is in our national interest to keep abreast of all emerging technology, and we may do this only by listening to all possible participants.

The symposium on which this volume is based was intended, in part, "to focus on the Centers as agents of change in the academic engineering culture and as catalysts for a broader, global perspective in the U.S. engineering enterprise generally." The global perspective is best served by providing mechanisms for all interested industrial companies to participate in the Center research program.

DELIVERABLES

The Delaware university-industry research program has a unique set of "deliverables" in the form of research and technology documentation, meetings and workshops, and trained personnel (Figure 3). Documentation of the emerging technology is provided through research reports, computer software, and the "Composites Design Encyclopedia" (unpublished; available upon request). Principal meetings include an annual workshop series, and many individual company briefing meetings at the Center. Education of university students as new practitioners in the field, as well as internship programs for students and faculty in industry, and industrial internships at the ERC comprise the personnel training segment of the program.

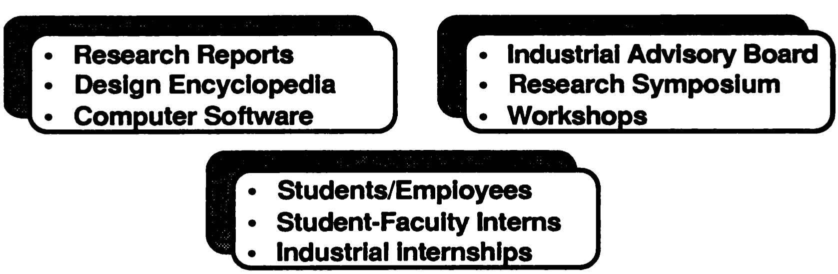


FIGURE 3 The industrial program provides high-quality deliverables.

Research and Documentation

Present research efforts in the Center for Composites Manufacturing Science and Engineering include over 80 individual programs of study carried out by students, faculty, and professional research staff. The projects fall into one of five research thrust areas: manufacturing and processing science, materials design, mechanics and design science, materials durability, and computation software and information transfer. Each project culminates in one or more Center reports, which are distributed to the industrial sponsors. The reports are drawn from graduate and undergraduate theses, doctoral dissertations, and journal paper submissions. Interim and final reports of separately funded contract research programs are also distributed to sponsors of the industrial program.

"Composites Design Encyclopedia"

A complete documentation of the state of the art is continuing as part of the industrial consortium program. The Center began creating the "Composites Design Encyclopedia" when the industrial program was initiated in 1978. The encyclopedia is aimed at providing new entrants to the field with a comprehensive view of the technology, giving technical specialists additional information on areas outside their range of knowledge, and identifying gaps in the knowledge base in composites technology (Figure 4).

The text is written by international experts in various disciplines within the composite materials community. The 1986

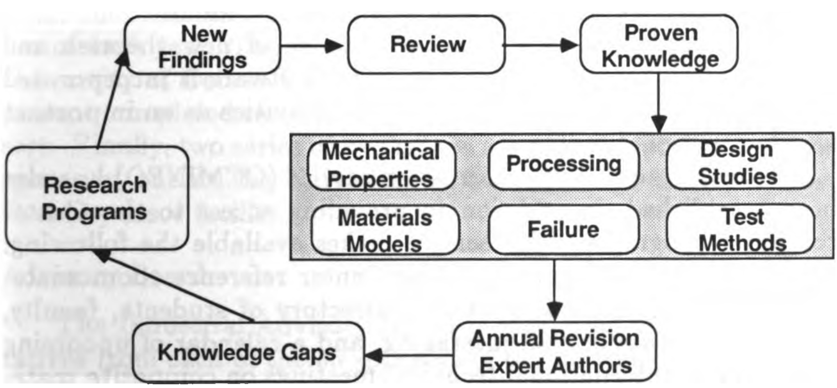


FIGURE 4 "Composites Design Encyclopedia" guides future research.

edition contains 3,600 pages in six volumes, including *Mechanical Behavior, Micromechanical Materials Modeling, Manufacturing and Processing, Failure Analysis, Design Case Studies,* and *Test Methods.*

Research results from Center programs and other research work are reviewed for inclusion in the encyclopedia. Once the technical merit of the findings is established, the material is added to the appropriate volume. The encyclopedia is reviewed annually by members of the Center's Industrial Advisory Board and by in-house and external experts to identify sections for revision. Equally important, this annual review serves to identify areas in the technology that are not well understood and that require further research effort.

Computer Software

The most innovative mechanism for technology transfer within the industrial program involves the development of computer software for the design, modeling, analysis, and optimization of composite systems. Virtually all the research projects carried out by the Center include the development of computer programs or subroutines.

The computer has become the primary vehicle for transfer and organization of information. In converting research models to user-friendly computer programs, the Center creates a record of the evolution of composites technology that is easily accessible to all organizations. This activity is highly regarded by our sponsors as a new and effective form of technical communication. It is credited with speeding up the acceptance of new theories and sophisticated methods of analysis. This software is incorporated into the workshops and into classroom activities as an important new instructional tool.

A telephone dial-up information service (CCMINFO) has also been established, in addition to providing access to the Center computer programs. This service makes available the following: student resumes; an index of the Center reference room materials; research report abstracts; a directory of students, faculty, and staff; electronic mail messaging; and a calendar of upcoming national and international technical meetings on composite materials. The dial-up system is available to anyone with access to a

CCMINFO
Electronic Information Service
James M. Byrnes (302)451-1520

CENTER FOR COMPOSITE MATERIALS
UNIVERSITY OF DELAWARE

Modem Use:
Sign on: CCMINFO
Sign off: LOGOFF

- **Research Report Abstracts**
- **Student Resumes**
- **Electronic Mail**
- **Technical Meeting Calendar**
- **CCM Library Index**

Dial-up Lines:
(302)451-6929
(302)451-6930
(302)451-6931

FIGURE 5 CCMINFO enhances communication with industry.

computer terminal and modem, although the use of Center computer programs is restricted to members of the industrial program. In order to enhance the use of the CCMINFO system, a business card for the system has been developed and widely distributed (Figure 5).

University-Industry Meetings

Three distinct university-industry technology transfer meetings are held each year, in addition to briefings to individual sponsors and potential sponsor companies. An annual meeting of the Industrial Advisory Board and its committees is held in September of each year. The Annual Research Symposium is held at the University of Delaware in conjunction with the board meeting to present completed research program results to the industrial sponsors. Finally, two series of workshops are presented exclusively for sponsors, one at the University of Delaware and one at a West Coast sponsor facility.

Advisory Board

The Industrial Advisory Board is composed of two representatives from each of the 35 sponsors of the university-industry research program. These representatives are the principal conduits of information transfer from the Center to the sponsor companies and from the companies to the Center. Seven committees of the board provide input into the areas of research programs; mechanisms for technology transfer; new computer software; facilities; issues surrounding patent and company affiliation policy; faculty, student, and general honors; and long-range planning. Each sponsor company has membership on two of the committees at a time; the companies rotate through each committee for a three-year term.

The board serves in an advisory role only. Control of the program is fully vested in the university, although the best interests of all participants are served through active cooperation between the university and its industrial affiliates. As was noted earlier, the major benefit to the ERC of the participation of industry is the contribution of real-world engineering problems for research. These problems are transferred to the Center through the advisory board members.

Three other advisory boards have been established to review Center activities. Membership on the Manufacturing Science Advisory Board (MSAB) is limited to representatives of corporations that provide significant financial support for the development of the Composites Manufacturing Science Laboratory (in addition to base membership in the industrial program). The primary responsibility of the MSAB is to advise the Center on the conduct of the research program in composites manufacturing science and the development of new manufacturing facilities.

The Science Advisory Board consists of a distinguished panel of scholars and scientists from government, academia, and industry with outstanding professional reputations in composite materials or a related field. It is the primary responsibility of the Science Advisory Board to offer impartial advice to the Center in scientific and engineering matters.

The Faculty Advisory Board is comprised of full-time faculty members who represent the academic disciplines that are active in Center programs. The Faculty Advisory Board advises the Center personnel in academic matters such as curriculum development, educational programs, and student resource allocation.

Research Symposium

The Annual Research Symposium is held in September of each year immediately following the meeting of the Industrial Advisory

Board. The program includes technical presentations, a poster session, computer software demonstrations and hands-on sessions, laboratory tours, a banquet, and a keynote address by the Medal of Excellence in Composite Materials award winner.

During the three-day symposium, 20 to 30 technical research papers are presented on completed projects. Students, faculty, and research staff present professional-quality reviews of their work. Documentation of the completed work takes the form of published theses, dissertations, and journal papers.

New research starts and in-progress research programs are discussed during an open poster session. Every project is represented in the poster session; attendees provide comments and guidance for approximately 75 researchers prior to the completion of the on-going research programs. This is particularly important in rapidly evolving technologies such as composites. Interaction with the industrial community takes place as the research progresses, providing new insights for the university participants while accelerating the acceptance and utilization of the new knowledge by industry.

Laboratory tours are provided to view new facilities at the Center. In connection with the laboratory tours, computer software demonstrations are also presented. A separate hands-on session is conducted for industrial sponsors to test the software packages developed at the university.

The Center for Composite Materials celebrated its tenth anniversary in September 1984 with an international symposium on composites science and engineering, and inaugurated a Medal of Excellence in Composite Materials. That medal is now awarded each year to an outstanding scholar or researcher in the field of composite materials who is selected by a panel of distinguished experts. The medal is presented during the Annual Research Symposium, and the award winner is invited to present the keynote address. This medal has become highly coveted by scholars in the field of composites all over the world.

Workshops

Two workshop series are presented each year for the industrial sponsors. Introductory and advanced topics are presented in concurrent sessions to address the needs of industrial engineers and scientists. Introductory material is offered to provide an orientation to the field for new engineers or cross-training for industrial personnel not presently in the composites area. Advanced topics are offered for current practitioners to extend their understanding of the state of the art.

One workshop series is held at the University of Delaware and one is hosted by a West Coast industrial sponsor. Attendance is simplified by having one series on the East Coast and one on the West Coast, so that oversubscription in either location is reduced. This year we added a poster session to the workshops in recognition of the great success of the poster session during the research symposium. Typical attendance is over 100.

The Annual Student Award Dinner is held during the workshops at the University of Delaware. The dinner recognizes the important contribution of the students to the program and shows the industrial participants the quality and breadth of our students.

Personnel Interactions

The most important product of the University of Delaware-Rutgers University ERC is students who become employees in industry, government, and academia. The transfer of educated and trained students from the universities to industry is the principal goal of the industrial program as well. In addition to direct student-to-industry transfer, the University of Delaware program includes internship programs for students and faculty in industry and internships for industry personnel at the ERC.

Graduate and Undergraduate Students

All engineering disciplines at Delaware are represented at the Center: chemical, civil, electrical, and mechanical, along with materials science. More than 70 graduate students are currently in the program working toward master's or doctoral degrees. These students are the principal researchers and authors of the research reports and computer software provided to the industrial sponsors.

An unusual undergraduate research program is under way in the Center, employing undergraduate engineering students as research assistants in the laboratory program. Undergraduates with excellent academic standing and who are highly motivated toward research and/or graduate school are enlisted in their sophomore year to work in this program. These students perform laboratory preparation and testing work part-time during the summer. During their junior year, the students work part-time in the laboratory environment while classes are in session and then go to work in industry for the summer between their junior and senior years. When they return for their senior year, these students are encouraged to perform independent research projects toward a degree with distinction (Figure 5).

Internships

In addition to the undergraduate research program, graduate and undergraduate student and faculty internships in industry are encouraged. Interns from industry to the ERC are particularly important in new and emerging areas to transfer technology to and from industrial sponsors.

Graduate students and faculty members are encouraged to work closely with sponsor industries that are interested in their research projects. Often, individual companies have the equipment and facilities needed for a particular phase of the ongoing program, and we have been highly successful in placing faculty and students in the industrial laboratories for research.

The Center for Composites Manufacturing Science and Engineering has a history of attracting outstanding engineers from industry as interns to reside in the Center. The program requests sponsor companies to send their employees to the university for a period of between 3 and 18 months, with their salary and living expenses supported by the industrial firm. The Center provides office space and the use of facilities for research on an open problem of mutual interest.

Industrial interns use Center equipment and computer software and often take advantage of the educational environment of the university. The current thrust of the Center is to attract interns with manufacturing experience. These new interns will be employed in helping to identify, acquire, and install appropriate manufacturing equipment for composite materials, and then in carrying out manufacturing-related research.

INDUSTRIAL MARKETING EFFORTS

The success of an individual Engineering Research Center is measured in part by the strength and growth of its industrial support program. A marketing effort may seem out of place in the academic community, but in this case it is considerably more than simply an advertising program. Rather, the successful marketing of the ERC program is a direct result of mechanisms of technology transfer to and from industry.

Briefings to individual companies on the activities and progress of the ERC and presentations made during technical meetings represent the major marketing thrusts of the Delaware program. Appearances in the popular and technical literature also place the Center in high profile. By itself, the naming of the Delaware-Rutgers program as a National Engineering Research Center has attracted significant industrial interest to the program. Increasingly important to our marketing are referrals from our existing sponsors and our alumni.

The Center for Composite Materials has participated in technical and trade expositions and shows for several years. The purpose of our appearance at trade expositions is not exclusively for marketing but, more importantly, to provide an additional avenue for technology transfer to the ERC in the area of emerging composites technology. The interaction between university representatives and exposition attendees or other exhibitors has been very fruitful. Furthermore, Center students assist faculty and staff at the shows, giving them added exposure to the changing technology. Often, the students are the best ambassadors; they are technically competent and highly motivated to interact and listen to industrial personnel while searching for barrier problems to solve.

PARTICULAR HIGHLIGHTS

The first year of the University of Delaware-Rutgers University ERC has been a major success from the standpoint of industrial interaction. The most prominent accomplishment of the Center was our success at attracting an outstanding new director from industry. Dick J. Wilkins was appointed director of the Engineering Research Center on January 1, 1986, after a 17-year technical career in composites technology development with the Fort Worth Division of General Dynamics. Prior to joining the Center, he was most recently the engineering staff specialist for composites technology, serving as internal consultant to the director of the Structures and Design Department at General Dynamics. He served as chairman of the Corporate Composites Committee and the Engineering Education Advisory Committee. He has been associated with the programs within the Center for several years through participation on the Industrial Advisory Board and was chairman of the Technology Transfer Committee of the board as a representative from General Dynamics.

Nine new industrial consortium members have joined the program since the establishment of the Delaware-Rutgers ERC. Since the current sponsorship fee for participation in the university-industry research program is $38,000 per year, the total increase is $342,000 per year. The nine new companies bring the total membership to 35. The parallel Composites Manufacturing Science Laboratory (CMSL) program has grown from two members to six. Each company contributes $100,000 toward equipment purchases in order to belong to the CMSL, so the new members have donated a total of $400,000.

In addition to direct financial support, four named graduate fellowships have been established through donations from industrial sponsors. We have commitments from sponsor companies for four to six industrial interns beginning in September 1986; two interns were in residence during 1985–1986. The Center also received $150,000 in equipment donations from existing sponsors.

SUMMARY

Since the Center for Composite Materials was founded in 1974, the composites program at the University of Delaware has been committed to the philosophy that effective technology transfer is vital to the advancement of composite material systems. Over the past decade, unique mechanisms have evolved and been refined to supplement the traditional means of interacting with sponsoring groups. The new Center for Composites Manufacturing Science and Engineering continues and intensifies that tradition.

Industrial interaction has a pervasive influence on the activities of the Center. Virtually every segment of the program is enhanced by participation of the industrial sponsors. The research program benefits from the insights and barrier problems provided for study, the educational program benefits from the pressure that industrial engineers and scientists place on the universities for well-trained and educated practitioners, and the technology transfer mechanisms are improved by the innovations emanating from industry.

The benefits of the Engineering Research Center to industry are equally rewarding. Critical fundamental research issues are addressed by the ERC in an atmosphere that is conducive to providing solutions to difficult problems. Furthermore, most of these research problems are industry generic: the solution of the problem is of interest to many different companies. New technology is transferred to industry rapidly and in ways that are immediately useful. Finally, new entrants into the emerging field are produced with the background and training necessary to enhance industrial competitiveness and provide a global perspective in the U.S. engineering enterprise.

Increasing Industry's Involvement: A Perspective from the ERC at Columbia University

RICHARD OSGOOD

The Engineering Research Center (ERC) at Columbia University, the Center for Telecommunications Research, was described in another paper in this volume by its director, Mischa Schwartz (see "Center for Telecommunications Research," Part II). It consists of four different entities or subcomponents: one on analysis, one on optical devices and materials, one on systems and new concepts, and one on very large scale integrated (VLSI) systems and circuits. Clearly, it represents quite a mixture of different research fields and disciplines.

With regard to industrial participation, rather than discuss the formal methods of industrial participation—which I think tend to be just that, formal things—I will emphasize what I think are the important *informal* aspects. I believe that, in the end, these are the important aspects.

The first requirement is that the Center has a very strong and diverse research program. I think that, ultimately, if the universities are just producing graduates but not really contributing innovative new ideas—if they are not respected leaders technically—they are, in effect, just rearranging the pieces on the board. This

This paper is based on remarks made in a panel discussion at the symposium.

simply does not work. Industry people, when they visit the university, have a feel that they are talking to someone who has technical authority.

The second requirement is that there be ease of contact. That may be a matter of geographical location, which we are certainly blessed with at Columbia, or it may be a case of just having good accommodations and making it easy for people to come to visit. Industry people are generally quite busy, and they do not want to spend much time shuttling back and forth on these exchange programs. That is a frequent concern of people from industry.

Another important aspect, and it is something that we in the university community are very aware of, is that there must be a commitment to the Center on the part of the university. Commitment may mean a reorienting of tenure committees, as was alluded to in a previous paper in this volume (see Alan S. Michaels, "Stimulating Innovation: Problems and Opportunities in an ERC Environment"), so that they understand the difference in project work versus individual work; or it may mean building new buildings, providing office space, or making sure that those faculty positions that were promised early, when the Center was only an idea and a proposal, are really delivered. Even something as mundane as parking space is very important.

The next informal aspect, one that is somewhat related to my point about having a strong research program, is that you must have research topics that are recognized as being important—that is, topics that, although they may not be relevant tomorrow, are clearly understood to be relevant in the next 10 years.

The next area I would like to mention relates to the types of industrial sponsors that a Center can have. At Columbia we focus on telecommunications research, and like other Centers, we have different grades of membership; but I think one of the interesting things that can be noticed is that there are different classes of sponsors. In our particular case it turns out that we have *users* of telecommunications components—for example, Merrill Lynch or Federal Express—and they have very different requirements and interests in the Columbia program than does a communications *provider* company such as AT&T. One group cares a lot about research and wants us to be looking far ahead into the future, because they are taking care of the immediate problems. The other type of company, the user, cares mainly about whether we are working with state-of-the-art equipment, so that they can immediately turn around and apply our results to their particular problems.

Another class among our sponsors is *manufacturers*; an example is Timeplex. They tend to fall somewhere in between the first two, so that their time line is a couple of years in the future. Each of these types of companies has different types of needs, different interests, and that is why a diverse program is absolutely essential for attracting the maximum number of sponsors, or for bringing in a lot of different people from the outside. So, if success means involving a lot of industrial sponsors, a Center must have a broad program.

DISCUSSION

Most of the discussion regarding the interaction of ERCs with industry (papers by J. J. Solberg and W. A. Dick) centered around the question of foreign participation and possible restrictions. Dr. Solberg said that his ERC is very cautious about foreign participation because the Japanese, in particular, excel at extracting technology in a detailed way. Other commentators noted that the emphasis on industrial support can conflict with the program goal of increasing U.S. competitiveness, if U.S. technology is drained away. Mr. Bloch asserted that this should not be controversial as long as the foreign company pays its fair share and the exchange of people and information is quid pro quo—i.e., fully two-way. In many cases, he believes, such exchange could help U.S. competitiveness more than hurt it. A related question dealt with whether the success of the ERCs could be measured in terms of products, patents, copyrights, etc. Both Dr. Solberg and Dr. Dick said that it is too early to evaluate the ERCs on the basis of patentable products; however, a major output is tools, in the form of computer software, of which there are already a number of copyrighted examples. Mr. Bloch stated that the ERCs will not be evaluated on this basis. Instead, the main criteria will be focused on education and industrial participation.

Increasing Industry's Involvement: A Perspective from the ERC at Lehigh University

JOHN W. FISHER

I would like to describe our experience over the past two years at Lehigh University in trying to develop industry support for and participation with our Engineering Research Center (ERC) on advanced technology for large structural systems. One of the problems we face is that we are dealing with a mature industry that is in distress. Furthermore, the construction-related industries, although they account for quite a large share of the gross national product, have never had a significant amount of their funds diverted to research and development. In fact, they are much more likely to spend vast sums of money on litigation than they are to look for better ways to prevent that from occurring.

Thus, we have a fragmented and diverse industry with no prior history of supporting significant research. During the past 30 years these industries have, for the most part, relied on the basic steel and cement industries to support research and to develop the knowledge base. However, it is now common knowledge that the in-house capabilities for research have diminished dramatically in the basic industries over the past three years. The companies have essentially eliminated most of their research capability. The same trend has, of course, brought a substantial decrease in the possibilities for financial commitment to external research.

This paper is based on remarks made in a panel discussion at the symposium.

At Lehigh University we have spent two years trying to overcome some of these problems. We convened a conference in January 1985, which about 40 industrial participants from 30 companies attended. We discussed directions that the proposed research program could take and obtained expressions of industrial support. When we were not successful in the first round of ERC competition, we met with key people from industry who had supported our effort. We found that there was still strong support for the Center. However, the distressed nature of these industries presented a continuing problem in terms of financial and industrial manpower support. That will continue to be a problem.

We have an educational and communication problem with many of the industries that we are trying to reach. Many companies have no individuals involved in research. Often, we are dealing with engineers burdened with problems. The manpower reductions among the basic steel producers and fabricators have been extensive. Many are just hanging on, trying to avoid bankruptcy. Hence, we have had to undertake a major selling effort in order to develop a support base. We have sent faculty teams into companies to discuss with them research possibilities and ways to support a research base. We do see some positive things on the horizon. We have had some industry commitments and indications that they will join our liaison program. However, we are going to have a continuing effort on our hands convincing industries that have not had a traditional history of research that they can benefit from research. We must convince them of the advantages of their participation with our ERC.

Increasing Industry's Involvement: A Perspective from the Industrial Research Institute

ROBERT STRATTON

I view the Engineering Research Centers (ERCs) as part of a continuing evolution of the initiatives to establish closer industry-university coupling.

Since the history of the established ERCs is really very short, the National Science Foundation (NSF) can draw on the experience gained earlier with 20 or so much smaller industry-university cooperatives (IUCs). Research Centers formed over two decades ago—e.g., the Polymer Processing Center at the Massachusetts Institute of Technology, the Center for Telecommunications at North Carolina State University, and the Center for Welding Research at Oregon State University—have now cut the umbilical cord to NSF and are heavily supported by industry. Why? Because they provide technology leases that could be used to solve various engineering problems encountered by the sponsoring companies.

Another example is the Semiconductor Research Cooperative (SRC), which now supports half of all the silicon-related work at universities; it is doing an excellent job of providing generic technology bases, technical information, and appropriately trained engineering for the U.S. electronics industry.

The Stanford Center for Integrated Systems (which is trying to marry electrical engineering and computer science, an imperative

This paper is based on remarks made in a panel discussion at the symposium.

for advancing electronic devices and the computers and other systems based on them), the Materials Handling Research Center at the Georgia Institute of Technology, and the Berkeley computer-aided design/computer-aided manufacturing (CAD/CAM) consortium are all similarly successful because they are responsive to specific industry needs.

While I recognize that the ERCs have a broader charter than the IUCs, particularly in the area of education and in fostering cross-disciplinary research, the experience gained from the success of the earlier activities can provide clues for increasing industry participation. For example, continuing and, indeed, increased industry support requires:

- industrial participation in setting overall goals;
- success in developing new and useful technologies;
- mechanisms for technology transfer; and
- production of high-quality engineers who have a feel for industrial activities.

Before coming to the symposium I had made notes on actions needed to meet these requirements. I found that a lot of my prepared comments are reflected in what is already going on in existing ERCs, as described by the various directors in Part II of this volume. My comments will help to emphasize the need for certain actions based on my perspective as an industrial research and development (R&D) manager.

The role of industry in helping NSF select winning proposals should be increased to help establish ERC missions based on national priorities. Companies should also participate with universities in articulating strategic goals for ERC proposals.

The ERC director should form and rely on a policy board, with industrial participants, for setting and evaluating progress toward specific goals. Qualified engineers should be chosen as industrial "mentors," based on the SRC model, to work closely with the engineering faculty in both a supportive and critiquing mode.

Industrial participants on ERC policy boards or technical advisory/review panels tend to be individual R&D contributors or managers. The introduction of some manufacturing, and yes, even marketing, people from industry could provide a whole new perspective on what is needed to do engineering research in those areas that have a chance of providing innovations.

Resources should be sufficient to fund research equipment as well as people and materials (a problem for some of the smaller centers formed in the past).

Industrial participants must have their own engineers directly involved in the ERC programs. (I know this is an industry rather than a university problem.) In turn, having professors spend summer on sabbaticals in industry may also be useful.

To communicate their approach and their findings, the ERCs must provide:

- workshops on modern engineering concepts;
- more general education (i.e., re-education) for engineers from industry; and
- opportunities for their graduate students to participate directly with the industrial participants so as to achieve a better understanding of industrial research.

Emphasis on manufacturing engineering is key in *all* the Centers to some degree. The establishment of manufacturability for engineering advances is clearly an important goal.

To enhance this nation's industrial competitiveness, the ERCs should involve science as well as engineering disciplines, e.g., condensed-matter physics, plasma physics, and theoretical and physical chemistry, as appropriate. Frequently, scientists can bring new techniques to bear on development or engineering problems. Many scientists are motivated to do this but do not know how to make the contacts. The ERCs (and, incidentally, the Presidential Young Investigators program) are excellent vehicles for involving scientists as contributors.

Finally, the ERCs need strong directors with executive support to provide the leadership needed for outstanding engineering research, for the desire to see the ERC's goals met, and for keeping up the motivation for interaction with industry. (The last item should be viewed positively as a source of exciting engineering challenges rather than as a need to offset declining NSF funds.)

Such a position could be a career problem for a professor in relation to the conventional university value system. Would these accomplishments get rewarded? Incidentally, it is essential that all the professors contributing to interdisciplinary activities be rewarded by a system that recognizes nondepartmental activities.

I know there is some concern in the universities that closer relations with industry could stultify creative research. There is a perception that the pendulum could swing too far and industry could play too large a role in forming university engineering and even science policy. We are a long way from that state of affairs, and I for one do not see it as a problem. I believe industrial participation can, and should, enrich university research and educational problems.

Increasing Industry's Involvement: A Perspective from the U.S. Department of Commerce

D. BRUCE MERRIFIELD

Some 90 percent of all the scientists and engineers who have ever lived are now living and working. Their number will double again in our lifetimes, and most of them will live outside the United States. We have to understand clearly that this is an historic event. Nothing like this has ever happened before. We are living in a time when facilities and equipment will become obsolescent at an increasing rate, while at the same time unparalleled opportunities are opening up to expand the global economy and raise the quality of life of every nation in the world. This is a unique opportunity for U.S. leadership. But it will require collaborative efforts. No individual company, no university, no individual organization can do it alone. To develop the next generation of advanced technology will require collaborative efforts, and it is critical that we begin to form these coalitions quickly and effectively.

Inevitably, we will stumble and make mistakes, but that is all right. At the Commerce Department, one of our major initiatives has been to get legislative barriers removed and eliminate the bureaucratic processes in Washington, D.C., that tie up federally funded technology and prevent it from being released into the private sector. The federal government spends about $55 billion a year on development of technology for health, energy, military,

This paper is based on remarks made in a panel discussion at the symposium.

and many other purposes. There are 28,000 government patents outstanding, of which only about 4 percent have ever been licensed. That is unfortunate. Our current legislation would free up this resource, providing the laboratories that are doing the work with the authority to license exclusively to individual companies and then receive the royalty stream back into the laboratory to further its mission.

The Bayh-Dole bill in 1980 and the 1984 Dole bill started this process, which I hope will be furthered by current legislation. Another barrier is the high cost of capital in this country, which is about three times higher than in Japan or West Germany. The new tax laws will further increase the cost of capital.

Also, we have identified about 100 regulatory barriers that need to be selectively modified to allow the process of collaborative efforts to go on.

We are currently going after Section 7 of the Clayton Act and Sections 1 and 2 of the Sherman Act—not necessarily with respect to mergers, but rather to clear the way for the collaborative manufacturing functions that are going to be required. Within a decade, much manufacturing will have to involve flexible, automated, computer-integrated systems wherein a given plant makes between 500 and 1,000 products for different companies in different industries, with shared ownership. Sister plants around the world will be programmable to make the same thing tomorrow. This is the wave of the future. But collaborative efforts on an international scale will be needed if we are to take advantage of our advanced technology and then work out joint venture arrangements with companies from foreign nations. The time scale for development can be accelerated, and additional market potential can be realized in each of the countries involved.

The United States, with only 5 percent of the world's population, was generating something like 75 percent of the world's technology a decade ago; but our share is down to about 55 percent now. In another decade it may only be a third, not because we are generating less (we will be generating a lot more), but because the other 95 percent of the world is going to participate. Every nation sees now that technology is the engine that drives the world economies and intends to participate. A continuous worldwide scan of technology developments is required, or we will fail to take advantage of seminal developments in other countries and/or we will do redundant work.

We have to understand that major forces of change now are operating, whether they are with or without us. If we understand them, we can structure positive and proactive responses, but it will require cooperation among all of us to do so.

DIRECTORS' DISCUSSION OF PROBLEMS

The chairman of the NRC's Cross-Disciplinary Engineering Research Committee, Don Kash, asked all those representing the first six Centers to describe the kinds of problems they had encountered in implementing ERCs within the existing university structure. The following obstacles and problems (in summary form) were mentioned in the ensuing panel discussion.

1. There appeared to be agreement that the most difficult problem is the enormous and sustained extra workload for everyone involved in a Center—particularly for the director and other executive-level people. Participants maintain their normal teaching and advisory loads, as well as a heavy research load; but they also have many administrative and coordinating responsibilities. A particularly time-consuming task is hosting the large number of visitors to the Center. In general, nearly everything about a Center is new and takes time and attention—what Dr. Hackwood called "nursing things through."

2. A common problem is the question of how to handle tenure for assistant professors involved in cross-disciplinary research. As Dr. Baras points out, "There is no way one can do this kind of research without being able to reward faculty at least equally for their interdisciplinary research as for their discipline-based research." The ERC at Columbia counsels its younger faculty to publish their results in the relevant disciplinary journals, focusing on telecommunications as the application area.

3. Space is another problem. Usually there is a finite amount of existing laboratory and office space, and if the new Center takes some of it over, one or more departments lose turf. Maryland's approach is to have numerous meetings with everyone involved—faculty, unit heads, etc.—to create a "joint venture spirit" that can soften the competitiveness and build a long-lasting relationship with the departments. Obviously, this takes considerable leadership ability.

4. To gain the goodwill and cooperation of the top administrators of the university (which is essential) requires a substantial "selling" effort to convince them that the ERC is a winning proposition for the university. Again, the involvement of deans and department chairmen from the beginning seems to be key.

5. Another aspect of the turf problem is budget. Whether to put proposals through the Center or through departments, how

to deal with credit—such questions must be resolved. In doing so, the Centers seem to rely heavily on the wave of enthusiasm that their establishment generates.

6. As the Centers succeed and mature, they will have to deal with the question of how big they want to become—i.e., what the maximum effective or manageable size is within the school of engineering. The Delaware Center is one that is already facing this question.

7. The intellectual problem of establishing a truly cross-disciplinary Center involving very different disciplines is one that is inevitably hard to overcome. The MIT Center has found that a workable approach is to structure projects in such a way that all participants—students, faculty, postdocs, etc.—have to increase their understanding of the fundamentals of the other disciplines involved.

8. Downturns in the associated industry present a serious problem for any Center. The ERC at the University of California, Santa Barbara, has already felt this pinch with the weakening of the microelectronics industry.

9. With respect to state support, those Centers located in states where their university is the strongest one or the only established one will have an easier time than Centers in new schools or in states where there are many strong competitor universities.

10. It is somewhat dangerous to become involved in university politics—and it adds further to the workload. But most ERCs will have to lead an effort to alter existing policies with respect to industrial interaction (patents, royalties, property rights, disclosure, etc.).

Part IV

ERCs AND THE STATE GOVERNMENTS

Remarks: The Importance of Government Policy

ARDEN L. BEMENT, JR.

As we all know, technology is becoming the great equalizer in the economic adjustment among nations. The pressures for technological excellence to ensure success in the marketplace are intensifying, especially for developing nations. They see that technology, combined with their low-cost labor and raw materials, can greatly boost their industrial competitiveness and world trade. Highly developed and developing nations alike are pursuing technology not only to improve their productivity, industrial competitiveness, and economic growth but also to boost national pride.

Consequently, the preeminent position that the United States has enjoyed in science and engineering since World War II is being more seriously challenged. While the United States still leads the free world in research and development (R&D) investment as a percentage of the gross national product (GNP), Western Europe and Japan are quickly closing the gap. With this leveling in technological capability around the world, one can pose the question: "Can national technological policies, or even transcontinental policies in the case of the European Common Market, be major forces in influencing the growth of new high-technology industries?" A major part of this question is the included question, "Who chooses?"

In this context it is useful to examine the emerging technology policies of the federal government. One might argue that while we have a national science policy we do not have a national technology policy. In fact, however, the federal government has long exercised de facto technology policies to meet national needs. These policies have led to the establishment of R&D funding agencies, national laboratories with national missions, and major programs within mission agencies to provide enabling technologies. These national investments in R&D over the past four decades have provided a strong national talent base in science and engineering and an extensive R&D infrastructure to pursue both national goals and industrial markets.

When one looks, however, for federal policies that target the technologies necessary to meet competitive challenges from abroad, one finds a significant gap. It is here that the federal government looks to the private sector to make the choices—that is, to select the needed technologies. In pursuit of commercial goals the federal policy role in the United States is reserved to improving the economic climate for technological investments. It does this by providing, for example:

- tax incentives for R&D investments;
- accelerated depreciation schedules for R&D equipment;
- small business R&D set-aside programs;
- modification of antitrust laws to permit limited R&D partnerships;
- assignment of federal intellectual properties to universities and small business firms;
- opportunities for industry to use special instrumentation and to conduct proprietary R&D at national laboratories; and
- other such provisions.

However, even in the case of choosing the key technologies needed for future industrial development, de facto technology policies are now emerging. The policy of strengthening the engineering research program of the National Science Foundation (NSF), which has led to the creation of the Engineering Research Centers (ERCs), is a manifestation of a technology policy to enhance the nation's industrial competitiveness. In selecting these Centers, careful attention has been given by both the proposers and selectors to establishing ERCs that provide the highest leverage for the nation's future economic development.

Also, we now find that over 40 states have proactively established university-industry partnerships to address regional strategies for industrial development, economic growth, and engineering extension services to small and middle-size businesses. In a sense these states have carried the practice of technology targeting, as practiced by the Ministry of International Trade and Industry in Japan, to a more decentralized form. In essence, these states are finding the means to leverage off the nation's science and engineering base generated at universities in order to pursue specific technology programs linked to regional economic development strategies.

What we should be asking ourselves is: "Will the new institutional models emerging in the absence of an explicit U.S. national technology policy be more effective and robust than similar models instituted by competing national governments?" In the following two papers, by Christopher M. Coburn and Walter H. Plosila, we have the opportunity to explore this question by examining state initiatives. They will examine how the Engineering Research Centers are meeting the needs of states for pursuing regional strategies for economic growth.

Role of the States in Supporting Technology Innovation

CHRISTOPHER M. COBURN

In this paper I would like to describe the activities and the issues facing states as they support technological innovation. I would also like to address the importance of cooperation between federal and state university-industry applied research initiatives.

It is not easy for the states to relate to the federal government. There is confusion over how they should get along. Questions are asked like: "Can we work together?" "Are we competitors?" "Who leads and who follows?" The real point, though, is that the roles of the states are changing. The traditional notion of exclusively federal support for research and development (R&D) has been left in the wake of over 500 state and local high-tech programs. In the last three years over $450 million has been appropriated at just the state level alone for the support of applied research. Although this support of R&D is a new role for state governments, what we seek from it is not. Dating back to 1839 in the state of Maine, states have had programs for economic development, essentially with the goal of creating jobs. The primary motivation for the states today is still to retain and increase employment.

The sober realization that, as one governor put it, "the application of scientific knowledge is the basis for economic expansion and diversification, it is the key to the formation of new businesses and the competitive survival of old ones," is largely the result of an intense re-examination of state strategies and priorities brought on by the recession of 1980–1982. At the end of 1982, Ohio alone had over 700,000 unemployed people. Clearly, the old strategies were not working.

Acknowledging that change was necessary, governors went looking—not to other states, to steal their foundries and production plants, but to learn. They discovered that several of their colleagues, most notably Governor Hunt of North Carolina, Governor Brown of California, and Governor Thornburgh of Pennsylvania, had embarked on programs that committed their states to technological innovation. This sharing of approaches continues today as Governor Celeste of Ohio chairs a National Governors Association Working Group on State Initiatives in Applied Research—*high-tech programs,* in the popular vernacular.

The goal of the Working Group is to coordinate strategies and to learn from each other. This exchange of information is vital to the states as they pursue sophisticated strategies to support university-industry partnerships. There are no established models that can adequately guide the governors. Indeed, many contend that it is the states which lead all other levels of government in the design of applied research programs.

This independence has led to a variety of state programs: venture capital funds, business incubators, endowed chairs, equipment subsidies, and research consortia. However, as each state pursues its own separate strategy, it confronts the same set of issues. As I mentioned earlier, the principal motivation for the states is jobs, but now governors cannot simply point to a new factory when legislators and taxpayers want to know where their dollars have gone.

Long-term research programs are directly counter to the tradition of quick return on state investments. Not only are legislators now being told to wait for a return but a whole new set of rules is being agreed to. Governors are asking them to forget the "peanut butter" philosophy of state government. Research excellence cannot be achieved by spreading dollars to every corner of the state.

This is not to say that governors have been consistently successful at selling what amounts to a fundamental change in state politics. The visibility and promise of the state-sponsored university-industry partnerships guarantee that politics will have its impact; but I would observe that the same is true in Washington, as congressional responses to university initiatives further erode the peer review process.

Daniel Koshland, editor of *Science* magazine, described the phenomenon in terms of a new particle. He named it the ***add-on,*** which later results in the ***catch-on,*** which is when Congress figures out what is happening and decides to cut back the funding for all federal research agencies.

Whatever the measure, it is the results that the state taxpayers are interested in. Each state program can demonstrate some short-term job creation and retention, but the real lesson is that adequate performance measures do not exist. Of course, there are process results; six consortia created, *n* number of university-industry research grants made, etc. These are indicators, but they remain intangible. On the whole, the state programs are still several years away from demonstrating real results.

Even the states that have been at it longest are having trouble with their performance measures. Two separate studies recently uncovered phantom jobs in published North Carolina job creation figures.

There are problems and there are issues facing each state, but my message here is that state programs are out there. They are evolving and they are dynamic. In Ohio, through our Thomas Edison Program, we have established $160 million in public/private partnerships to support technological innovation. Every major university in the state and over 260 corporations are involved. The program builds on Ohio's strengths and at the same time establishes Ohio in emerging industries. The bipartisan statewide enthusiasm and support it has received from each sector of the state, particularly from industry, is a credit to Governor Celeste, who conceived the program in 1983, and to the Ohio legislature, which funded it at such a significant level.

If such initiatives are to truly be effective, however, creative ways must be found to promote coordination between the state technology programs and the Engineering Research Center (ERC) program of the National Science Foundation. The same goes for whatever coordination can be pursued with the new Department of Defense initiatives.

We may find a very instructive lesson in the agricultural extension model. Although the high value of the dollar has brought real hardship to the American farm, U.S. agriculture is still the world's most efficient industry. A more modest goal was probably intended when the Morrill Act was passed 125 years ago, establishing a nationwide agricultural strategy. The goal then was to stimulate agricultural innovation and to carry its results to the "furthest reaches of dusty farm roads."

Economist Lester Thurow attributes the success of this original university-industry cooperative program to effective coordination at the federal, state, and local levels of government. There are encouraging signs today that a similar success can be achieved in technology innovation. The challenge, I believe, is in systematic exchange at the policy level. If this can take place, both the goals of the ERC program and those of the state initiatives will be enhanced.

DISCUSSION

Mr. Coburn was asked a number of questions about the mechanics of Ohio's state programs in support of innovation. He explained that the state requires a minimum one-to-one cost sharing for each state dollar, the philosophy being to induce investments from the state's industries. Grants are made directly to universities; in the case of consortia, the funds are held by the consortium in a separate account, and the state approves drawdowns when matching funds have been obtained. In terms of the relative degree of access of public and private universities to these funds, Mr. Coburn said that this has generally not been a problem—although in the Research Challenge Grant program a limit of 20 percent of the funds was set for private universities. He explained that Ohio expects to capitalize on the new ERC at Ohio State University by finding ways to promote cooperative research between it and other manufacturing research centers in the state.

Engineering Research Centers and the Regional Economy

WALTER H. PLOSILA

INTRODUCTION

Increased interest is being shown throughout the United States and the world in the need for industry to be internationally competitive in technological innovation. In the United States, particularly, a second new Sputnik-type challenge is facing our economy—that is, whether the United States can be competitive in a world economy. While the challenge may be as severe as that during the Sputnik era, the general populace has still not seen it in quite these terms. Indeed, government, business, industry, and academia have not rallied together on the grand scale seen in the past to deal with the present situation. They have not done so for a number of reasons, but the most severe barrier is that the goal is amorphous rather than specific. A whole series of sectors of our economy are attempting to stay on the cutting edge of product development. Our private sector free enterprise system makes it difficult to develop a consensus on what should be the legitimate governmental role in this international competition (in contrast to the creation of the National Aeronautics and Space Administration [NASA], to meet the earlier challenge). Nor can the response be a simple, one-time activity; most observers suggest that the product life of almost everything produced is becoming shorter and shorter, necessitating the need for industry to constantly adapt its products—to new materials and new manufacturing processes—and upgrade its work force to use such processes and products. This means an ongoing effort—indeed, almost a total cultural adaptation—without a set time limit or completion date on which one can say, "It is done; we are finished!"

As part of the national self-examination of America's competitiveness in technological innovation, increased recognition is being given to improved communications, exchanges, and other joint arrangements between our higher education institutions and the private sector. States and localities, as they go through economic transitions, are recognizing the role that higher education can play in regional economic development. While these roles vary, all emphasize the importance of new partnerships among business, higher education, and government. The National Science Foundation's (NSF's) Engineering Research Center (ERC) initiative complements these state and local efforts.

Various models and approaches are being pursued by government at all levels (federal, state, and local), by private sector firms, and by higher education institutions. These approaches vary in: the degree to which the private sector is involved and the depth of the collaboration, funding support, the interdisciplinary nature of the effort, the comprehensiveness in approach, mission, location, and locus of leadership. But all are presented as ways in which higher education can assist in helping to improve the long-term competitiveness of this country in technological innovation.

MODELS AND APPROACHES TO REGIONAL ECONOMIC DEVELOPMENT

Many states and localities have sought to replicate the results of the economic explosion along Route 128 in Boston, in North Carolina's Research Triangle, or in California's Silicon Valley. In all three instances, strong research universities are nearby and serve as a magnet for industry and as the basis for nurturing new start-up firms on the cutting edge of technological innovation.

While many areas of the United States are attempting to emulate these examples, linking the assets of their higher education institutions to economic development efforts, the models or approaches differ considerably. States and localities recognize that higher education is a resource or asset and a source of comparative advantage to those jurisdictions in determining their long-term destiny. Whether that resource is viewed in terms of the value of its research and development, its education and training mission, the access it provides to a cadre of skilled professional and technical personnel, or the likely firm start-ups and product development that can lead to commercial application depends on the particular jurisdiction. But in most instances these approaches see higher education in a broad contributory role with respect to regional economic development.

Similarly, NSF's Engineering Research Centers have multiple benefits, not simply as centers of research and development excellence, not simply as a place for new types of cross-disciplinary education and training, but also as magnets for attracting and spinning off products and industries. That certainly is the perspective that the Commonwealth of Pennsylvania has, and that is why we have helped finance facilities to house the two new Centers to be located in Pennsylvania at Carnegie-Mellon University and Lehigh University.

Briefly, I will describe five models of industry-university-government partnership being practiced in this country:

1. *Centers of Excellence*

This approach usually involves establishing centers of excellence within certain fields, either by individual institutions or in a consortium arrangement. Industrial linkages are usually industrial affiliates; rarely are they sponsored or contract research. Sponsors see these centers as magnets to attract firms. The focus is generally on fundamental research, not development; outside funding is not tied to individual projects but is provided to the center itself; and private sector collaboration usually occurs through participation in one or two seminars a year and through opportunities to suggest the general areas in which they would like to see research undertaken.

2. *Information Dissemination*

This approach involves establishing an information dissemination vehicle to share knowledge on the latest developments in research and science with the private sector. Information dissemination/technology transfer vehicles have had federal sponsorship (such as by NASA), and a few states are establishing an industrial extension service within their engineering schools modeled after the successful U.S. Agricultural Extension Service. This approach is mainly informational, with considerable restrictions on how much "hands-on" technology transfer is undertaken. Private sector involvement, as in centers of excellence, is usually through advisory boards, participation in seminars, etc.

3. *Entrepreneurial Development Education and Assistance*

This approach generally involves development of entrepreneurial education and training centers, small business development centers, and business and technology centers usually tied to a university's business and engineering faculties. Courses and seminars are provided, as well as technical assistance to entrepreneurs. In some cases, incubator space is provided. This model focuses primarily on a university's education and training mission.

4. *Project Grants*

This approach involves providing direct project grants, either directly through a public agency to joint university-industry projects or through a consortium of business and university interests. The wide variety of approaches in this area generally precludes making generalizations. However, the general mode seems to be one of giving funds to a university, which then matches them with other funds from the private sector, with funds remaining at the university for research and development work.

5. *Comprehensive Consortium Arrangements*

This approach generally attempts to undertake several objectives including interdisciplinary centers of excellence, close collaboration by the private sector in project selection and execution, and activities that relate to training and education of the future work force, as well as research and development and entrepreneurial development. In essence, it includes components of the four preceding models with an emphasis on private sector collaboration.

Obviously, all state and local approaches do not readily fit into only one model. But these five approaches help to put into context the ways in which higher education institutions can contribute to regional economic development.

PENNSYLVANIA'S BEN FRANKLIN PARTNERSHIP EFFORTS

In 1982, Pennsylvania's governor, Dick Thornburgh, proposed the Ben Franklin Partnership (BFP). The original program administered by the Ben Franklin Partnership Board—the Challenge

Grant Program for Technological Innovation—now has a three-year track record. The program was designed to build partnerships between our outstanding higher education institutions and the private sector. The program is operated through four Advanced Technology Centers located in Pittsburgh (Carnegie-Mellon University and the University of Pittsburgh), State College (Pennsylvania State University), Allentown-Bethlehem (Lehigh University), and Philadelphia (University City Science Center—Penn, Drexel, and Temple). While these Centers are located at research universities, they are operated as consortia through policy boards composed of a number of higher education institutions in each region; business, labor, and local economic development groups; and others.

Each of the four Ben Franklin Partnership Advanced Technology Centers undertakes joint projects with the private sector in three areas: (1) research and development, (2) education and training, and (3) entrepreneurial development. In the area of research and development, each of the four Centers has three or four centers of excellence, such as computers and robotics at the Carnegie-Mellon University-University of Pittsburgh Center or computer-aided design/computer-aided manufacturing (CAD/CAM) at the Lehigh University Center. These centers of excellence are funded through a series of identified projects with one or more private sector firms that must provide matching funds first. State funds are provided second. Education and training projects include projects at liberal arts colleges as well as universities, and emphasize interdisciplinary approaches such as the manufacturing technology program at Lehigh or the Robotics Institute at Carnegie-Mellon. In some cases, they result in joint projects between a research university and community colleges, such as one recent project whereby the research university assisted five community colleges in establishing CAD/CAM technician programs to replace draftsmanship programs whose graduates were not in demand by the private sector. The community colleges could not afford the expensive equipment they can now tap into at the research university through terminals. In the area of entrepreneurship, our Centers help support small business incubators where start-up firms can undertake product development or manufacturing and have access to the facilities and faculty of the university.

In short, the Ben Franklin Partnership is a comprehensive consortium model that includes centers of excellence, technology transfer/information dissemination, project grants, and entrepreneur education and training components.

This approach was selected for several reasons:

- It provides ways to assist industry whether they are traditional in nature or need process technology to improve efficiency or competitiveness or new industries needing product technology to enter new markets.
- It takes advantage of Pennsylvania's major research universities and their comparative expertise without putting emphasis more restrictively on only one research and development (R&D) area.
- It encourages multi-institutional and multidepartmental approaches to meeting problem-solving issues; the applied emphasis and private sector project sponsorship gives greater assurance of meeting the needs of the private sector. Consortium arrangements and cross-disciplinary pooling of resources better address identified needs.
- It provides a decentralized, results-oriented design whereby private sector-university partnerships are formed from the "bottom up" rather than the "top down," with local peer review systems used to select projects competitively.

Whereas the federal government may address the entire nation without worrying whether federal tax dollars result in external spillover benefits to another jurisdiction, state governments are interested primarily in accruing benefits to their jurisdiction. State technological innovation programs such as Pennsylvania's are directed ultimately at creating and retaining jobs. They are designed to do this in several ways:

- Building centers of excellence in certain areas of comparative advantage can attract industry to an area, as Research Triangle (N.C.) has demonstrated. Indeed, the success stories of North Carolina, Boston, and Stanford (Silicon Valley) may not have occurred had not federal laboratories and/or defense spending been present at each location.
- A nucleus of outstanding faculty and graduate students can be encouraged to spin off their ideas into new products and new firms, as has been so well demonstrated at Stanford and Boston.

- Technology transfer, while still a practiced art rather than a precise science, can help existing firms in a region to modernize, improve their efficiency, and ultimately survive—if not expand.
- Upgrading the existing work force and graduating a trained and educated work force reduces the costs of firms doing business in a region and enables existing and new firms to utilize the best-trained talent available.

It is clear that federal initiatives and those of the states and localities can indeed complement each other, provided there are shared understandings. States and localities are primarily interested in their regional economies; the federal government has traditionally been interested in basic science, fundamental knowledge, generic education, and training. These two perspectives need not be in conflict with each other. Indeed, the two perspectives naturally complement one another.

Pennsylvania's Ben Franklin Partnership Centers, in their efforts, do complement the objectives of the Engineering Research Centers. Both are interested in problem solving; we are trying to encourage a greater private sector-university interface, and also to encourage cross-disciplinary and nontraditional education and training approaches. I doubt if state financial support is going to be discouraged by NSF. We recognize the economic benefits brought to our state and regions by the siting of these new federally funded research centers. Our financial support is being provided through a special line item for advanced technology facilities, so that funding is directed at improving the facilities in which our Engineering Research Centers will operate. One of our two Engineering Research Centers is also obtaining funds from the BFP Challenge Grant program for matching program dollars.

The Ben Franklin Partnership has had a number of major accomplishments in its first 34 months, including the following:

- State funds of $50.3 million have generated $169.9 million in private and other matching support in the first three years of the program.
- State funds of $21.3 million in 1985–1986 have been matched by $80.9 million in private and other funds, for a total output of over $102 million for 1985–1986 alone. It is the largest state technological innovation program in the country, on an annual basis, and the one with the most matching support from the private sector.

• In less than three years, the four Ben Franklin Partnership Centers have shown impressive job creation results. They have:

— assisted in the start-up of 244 firms, creating 1,308 new jobs and retaining 108.5 jobs;

— helped 175 firms to expand, creating 1,219 new jobs and retaining 452.5 jobs; and

— helped 95 firms to retain 1,637 jobs.

• In total, the four Ben Franklin Partnership Centers have helped 514 firms to create 2,527 jobs and retain 2,198 jobs, for a total of 4,725 jobs—all in less than three years.

• The four Advanced Technology Centers report 625 new products, processes, or services offered or under development as a result of BFP-assisted technology development efforts.

• Assistance is being provided to 20 of the 23 small business incubators now in operation in Pennsylvania. Eight BFP-supported incubator feasibility studies are currently under way, and five previously funded incubator projects are either looking for suitable sites or rehabilitating buildings as incubator facilities.

• BFP-assisted projects have attracted over $33.4 million in equity venture capital investments.

• In 34 months, one firm is already making royalty or licensing payments to a Center. Sixteen patents have been issued related to BFP-funded research and development activities.

• The Advanced Technology Centers have helped 644 entrepreneurs who wanted to participate in the federal Small Business Innovation Research (SBIR) Program. Twenty-nine awards totaling more than $1.9 million were made to firms assisted by the Advanced Technology Centers; Pennsylvania ranked fourth in the country in SBIR awards in 1985—right behind California, Massachusetts, and Virginia.

• Over 1,700 firms have been involved in the Ben Franklin Partnership, and 123 of Pennsylvania's degree-granting higher educational institutions have been involved in the program.

• The Ben Franklin Partnership has assisted us in attracting new federal research laboratories to Pennsylvania. In addition to the two NSF Engineering Research Centers, we have attracted (1) the Department of Defense Software Engineering Institute to Carnegie-Mellon University; (2) the nation's fifth national supercomputer center, as a joint center of Carnegie-Mellon, the University of Pittsburgh, and Westinghouse; and (3) a NASA bioprocessing and pharmaceutical research center at the University

City Science Center in Philadelphia. In each case, state funds have been provided, usually over a multiyear time period, including $6 million for the supercomputer center, $1 million for the NASA center, $4.5 million in grants and $22 million in loans for the Software Engineering Institute, and $2 million each for the Engineering Research Centers at Carnegie-Mellon University and Lehigh University.

ADVANCED TECHNOLOGY FACILITIES PROGRAM

Let me make a few observations as to how we determine state financial support for attracting federal research facilities.

The Commonwealth of Pennsylvania does recognize that to attract major federal research centers or research centers representing consortia of major private firms, states must provide assistance in addressing facility needs. In determining whether we will financially support a federal research center, we require that a proposed project meet all of the five following conditions:

1. *The proposed facility has or will receive designation as a major federal research laboratory or a facility serving multiple private sector firms through some consortium arrangement.* Small center facilities that will not place Pennsylvania colleges and universities in a position to serve as national centers of excellence will not be considered. The amount of state funding support provided will be relative to the budgetary scope of the proposed facility and its proposed uses.
2. *The proposed facility will be used for activities within the same R&D area as that of its respective Ben Franklin Partnership Advanced Technology Center's emphasis or will result in redefined emphases by the Center.* This condition is intended to emphasize the linkages of this program to the Ben Franklin Partnership Challenge Grant R&D efforts and to encourage colleges and universities to focus their efforts on facility enhancement that will result in the development of a select few national centers of excellence in which Pennsylvania will have a comparative advantage.
3. *The proposed facility will be used in a fashion that shows sufficient private sector financial support and commitment.* There must be indications of private sector interest and involvement both in development of the facility and in utilization of the resources and output of the facility.

4. *The proposed facility will be used for activities that have the potential to lead to commercial applications.* The proposed uses of the facility must show a potential for commercial applications and, consequently, job creation.

5. *The proposed facility will require state financial assistance to address a financial gap that cannot be addressed by other funding sources.* State funds must serve as part of a larger financial package, with leverage being a major factor in consideration of the amount and share of state support to be provided to any individual project.

NEXT STEPS

The National Science Foundation's Engineering Research Center can be an important spur to and a component of a regional economic development strategy. I would encourage those of you now operating Engineering Research Centers to recognize the important economic development role you can play, and to develop ongoing working relationships with your business community and with local and state economic development organizations. For those of you who wish to obtain such Centers in the future, I would suggest that you structure such relationships as you develop your proposal.

Technological innovation is integrally linked to economic growth. Technological innovation does not simply cover research and development. It must also address entrepreneurial aspects, that is, a culture that encourages risk-taking in a complex and unstable world. The exciting number of different approaches being used to spur technological innovation suggests a recognition that new ways of doing business are essential if we are to meet the challenge of world competition. Comprehensive approaches addressing the needs for a skilled work force as well as research and development are essential. A long-term perspective is necessary if we are to improve our long-term economic prospects. There is no single model of an Engineering Research Center, and there will be no single model of how it has an impact on regional economies. What works with one type of firm in a business-higher education partnership may not work with another type of firm, necessitating flexibility, adaptability, and a willingness to develop new and different relationships.

Pennsylvania's technology programs and the National Science Foundation's Engineering Research Center initiative both express the conviction that the pairing of research and innovation is critical to economic growth and to meeting our modern-day Sputnik challenge—international competition for leadership in technological innovation. Ninety percent of the scientific knowledge in the basic sciences has been generated since 1950. As that knowledge moves from the laboratory to the marketplace it transforms what we make, how we make it, and who makes it. The ability to compete in the technological revolution also depends on the availability of skilled professionals and technicians. Since 90 percent of 1990's workers and 75 percent of the workers of the year 2000 are in the work force today, new approaches to re-education, upgrading, and career adjustment will have to be taken by our higher education institutions. Engineering Research Centers can certainly assist in this effort, with respect not only to the practicing engineer but for our future work force as well.

The challenge of technology leadership now before us requires us to consider new roles and responsibilities. Those involved with the ERCs are on the cutting edge of what these may be. Colleges and universities have as a fundamental mission the education of the student. Their reward structures, including tenure, do not always encourage involvement in such business-education partnerships. There are activities that the university should not and probably cannot perform, such as operating as "job shops." There are a wide variety of relationships that can be developed, depending on the attitudes of different institutions, their strengths, and the needs and desires of their potential private sector participants. All of us should experiment, we should test new ideas and new approaches. Our country's future competitiveness depends on programs such as the Engineering Research Centers.

DISCUSSION

Dr. Plosila was asked whether, in his view, there is a potential for warping the university and altering its basic mission with the goal of economic development through state-supported initiatives. He replied that this was not likely to occur, for several reasons: most of the state programs are not very large (about $100 million statewide is the largest); participation is strictly voluntary for universities and for individual faculty members; the programs are very competitive, so that high quality can be assured; and the university has an option to veto any project or arrangement. Nevertheless, Dr. Plosila conceded, there is room for concern as to whether these programs provide enough support for fundamental research, or just "live off the seed corn" by doing applied work. His state's programs try to maintain a balance in that regard.

Part V

MOVING INTO THE FUTURE

Advanced Combustion Engineering Research Center

L. DOUGLAS SMOOT

INTRODUCTION

Why Combustion?

The United States's basic and high-technology industries are dependent on an adequate supply of energy, the production of which depends in turn upon combustion technology. The majority of the top 20 Fortune 500 corporations in the United States have some direct relationship to combustion. Their interests and products include automobile engines, gas turbines, fossil fuel gasification units, generation of industrial and commercial power, diesel engines, and propulsion systems. The future survival of these industries will relate in part to their ability to utilize more efficiently, through advanced combustion technology, our nation's readily available, low-cost fuel resources.

Several formidable roadblocks impede the realization of these critically needed developments: (1) use of outdated technologies and design methods; (2) long market-penetration times for new combustion technologies; (3) environmental and operational problems in the utilization of low-cost, low-grade fuels; (4) insufficient understanding of combustion fundamentals; and (5) lack of communication, collaboration, and cooperation among investigators in academic, industrial, and governmental research and development organizations. The removal of these roadblocks requires an organized, concerted effort that gives careful attention to the following priorities: (1) application of advanced, computer-aided design (CAD) methods for development of more efficient combustion systems, (2) efficient, clean use of available, low-cost fuels, and (3) removal of hazardous wastes. Combustion research required to address the priorities includes (1) development of reliable, robust computer models for combustion systems of interest to industry; (2) understanding of mechanisms of solids combustion, pollutant formation, mineral behavior, and soot formation; and (3) understanding of the relationships between fuel properties and conversion. The Advanced Combustion Engineering Research Center (ACERC) at Brigham Young University (BYU) and the University of Utah (U of U) has been organized to address these needs.

Objectives of the Center

Since combustion is a very broad field, a focused effort is essential in order to make a significant contribution. The ACERC's research program has been designed to address such priorities and to remove key roadblocks. The principal objective of the ACERC is to develop, evaluate, and implement (within five years) advanced computer-aided design methods in U.S. industry, with emphasis on clean and efficient use of low-grade fuels. Table 1 lists several

TABLE 1 Typical Industrial Uses of Computer-Aided Design Combustion Technology

Evaluate general characteristics of reactor
Extrapolate test data
Plan test program
Evaluate options technically
Evaluate advanced concepts
Evaluate impacts of fuel changes
Evaluate impact of reactor changes
Evaluate impact of changes in test conditions
Support reactor design
Support reactor control development
Support reactor optimization
Evaluate pollutant control (SO_x, NO_x, particulates)

TABLE 2 Examples of Applications for Advanced Computer-Aided Combustion Design Technology

Small combustors
Industrial steam generators
Utility boilers
High-pressure entrained gasifiers
Fuel burners
Cement kilns
Gas turbines
Coal-oil-fired furnaces
Coal-water-fired furnaces
Research reactors
Mixed gaseous solid fuels
Ceramic-lined furnaces
Water-wall furnaces

potential industrial uses for this new technology, while Table 2 shows examples of various types of combustion systems to which this new technology will apply. Our approach is to integrate kinetic and mechanistic data, physical and chemical fuels property data, and process performance characteristics into comprehensive state-of-the-art computer models to be used in the evaluation, simulation, design, and optimization of advanced combustion processes. We believe that a fundamental systems approach applied to a few carefully selected systems will have wide application to many important combustion problems.

Activities and Products

The projects of the new Center will include (1) new computer-aided design combustion technology, (2) new understanding of combustion mechanisms and their relation to fuel properties, and (3) students educated in the fundamentals of combustion engineering who can solve a wide range of problems. While combustion research is presently strong at the participating universities, the development of the Center will provide for major new thrusts in research. New activities addressed by the Center include (1) a strong focus on fundamental research aimed at improving in significant ways the international competitiveness of the United States in advanced combustion technology; (2) close cooperation among productive laboratories at the two universities, thus promoting interdisciplinary research with a common focus; (3) significant new financial support for research and engineering education from the universities, the state of Utah, and several national industries over the five-year study period and beyond; (4) a broadening of research investigations to explore new combustion technologies (e.g., catalytic combustion or solid waste combustion) from an interdisciplinary perspective; (5) access to high-capacity computer facilities, sophisticated instruments, and diagnostic equipment that will permit new investigations; (6) close cooperation with several industrial companies through interchange of personnel, annual conferences, and advisory meetings to promote the transfer of new technology; (7) new approaches to and courses in engineering education relating to combustion; and (8) close cooperation with Sandia and Los Alamos National Laboratories through the interchange of information and personnel as well as sharing of equipment and facilities.

CENTER ORGANIZATION

The organizational structure of the ACERC is illustrated in Figure 1. Each of the university programs is administered by an associate director (Calvin H. Bartholomew at Brigham Young University and David Pershing at the University of Utah). Each campus also has coordinators for academic and technology transfer programs. The directorate meets regularly, as do ACERC campus organizations. A secretary has been hired and space for a new office complex, which includes five offices, a conference room, library, and reception area, has been designed. Completion is projected for this fall.

External interchange is accomplished through two councils, the Executive Advisory Council and the Technical Review Committee. The Executive Advisory Council consists of seven distinguished individuals who bring extensive executive and research experience in the energy field from industry, government, and academe. The council provides general direction on the focus of our research and academic programs related to industrial needs. The council met for the first time on campus in early June 1986 to review general program plans and objectives.

The Technical Review Committee has responsibility for recommending technical directions and for evaluating specific research program work statements. Members of the committee are active in a wide range of combustion-related research in university, industrial, and national laboratories. This committee also met on

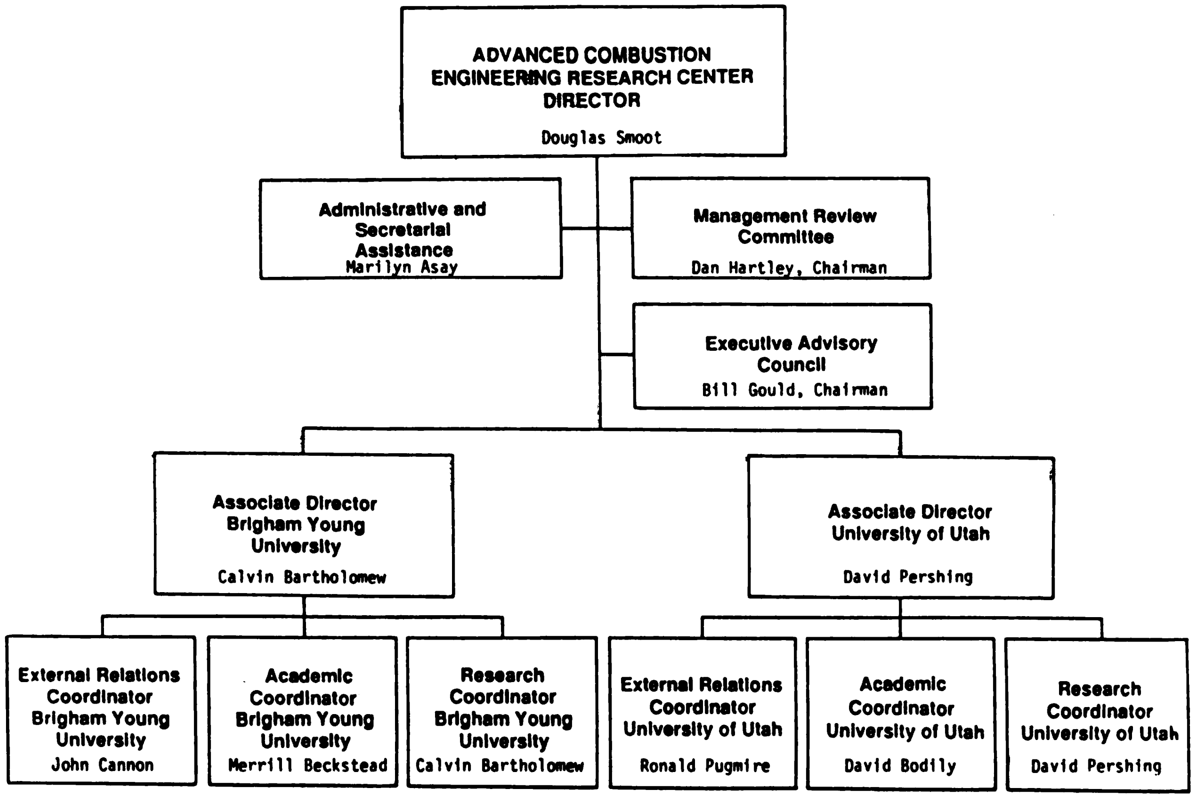


FIGURE 1 Organization of the Advanced Combustion Engineering Research Center.

TABLE 3 Key ACERC Investigators

Faculty Member	University	Department	Research Area
Calvin Bartholomew	BYU	Chem. Eng.	Physical structure of fuels/catalysis
Merrill Beckstead	BYU	Chem. Eng.	Modeling--reaction rates
Angus Blackham	BYU	Chemistry	Minerals--inorganic chemistry
David Bodily	Utah	Fuels Eng.	Fuels preparation
John Cannon (2)[a]	BYU	Mech. Eng.	Particles distribution--fouling and slagging
Henry Christiansen	BYU	Civil Eng.	Computer graphics
Geoffrey Germane	BYU	Mech. Eng.	Process data
David Grant (1)[a]	Utah	Chemistry	Fuel chemistry--nuclear magnetic resonance
William Hecker	BYU	Chem. Eng.	Physical structure of fuels/catalysis
Paul Hedman (4)[a]	BYU	Chem. Eng.	Process data--laser diagnostics
George Hill	Utah	Chem. Eng.	Fuel characteristics--reactions
Milton Lee	BYU	Chemistry	Fuel structure--supercritical chromatography
Henk Meuselaar	Utah	Fuels Eng.	Fuel structure
David Pershing (3)[a]	Utah	Chem. Eng.	Pollutant formation
Ronald Pugmire	Utah	Fuels Eng.	Fuel chemistry--nuclear magnetic resonance
Philip Smith (5)[a]	BYU	Chem. Eng.	Modeling--code integration
Douglas Smoot	BYU	Chem. Eng.	General-reaction processes
New Faculty Member	BYU	Chem. Eng.	Modeling--code integration

[a]Chairman of Working Group. Numbers in parentheses correspond to thrust areas in Table 4.

campus for the first time in June 1986 to formulate recommendations regarding the Center's research programs. The research interests of key faculty from the two universities who will participate in ACERC programs are summarized in Table 3. These faculty represent six departments in five colleges at the two universities.

RESEARCH PROGRAM

Research Thrusts

The Center involves a cooperative effort among two national laboratories, 19 industrial organizations, and the two universities in a concerted effort to address the priority combustion research problems identified above. Physical and chemical components (submodels) required for the computer-aided combustion design technology products are illustrated in Figure 2. These components include gaseous turbulence, gaseous reaction, particulate/droplet

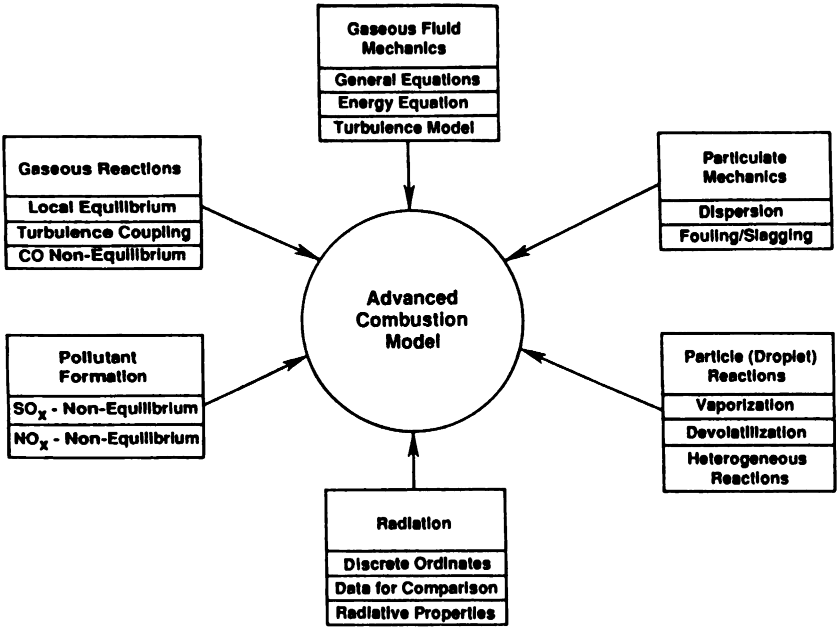


FIGURE 2 Elements of advanced CAD combustion technology.

dispersion, particulate/droplet reaction, radiation, NO_x/SO_x formation, and mineral matter behavior. Each of these areas is, in its own right, a major research area. It is therefore essential for the ACERC to identify those research projects that are the most important to the achievement of the principal objective. Research is also required to integrate, evaluate, apply, and implement the new technology. Figure 3 illustrates these tasks in the context of model development. Here also, essential tasks have been identified for initial consideration.

Research projects will be focused in six fundamental thrusts:

- relationships of chemical and physical structure and characterization of fuels;
- fuel minerals, fouling, and slagging processes;
- pollutant formation mechanisms and submodels;
- process characteristics/model evaluation;
- comprehensive model development; and
- exploratory areas.

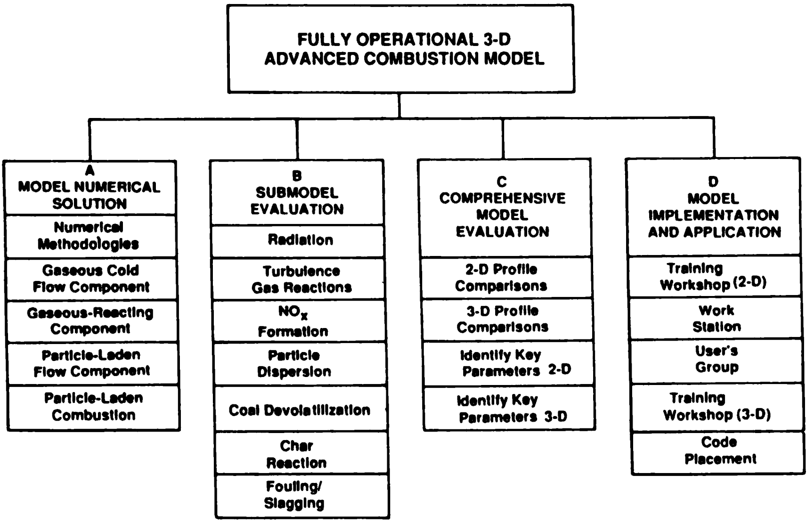


FIGURE 3 Development of comprehensive design technology.

The first five of these areas are the key elements needed for completion design, optimization, and control of advanced technology combustion processes. Three research subjects, specifically identified by a blue ribbon panel appointed by the Department of Energy, are among the potentially most productive for the near-term and will receive particular emphasis. They are (1) comprehensive and generalized modeling of coal combustion processes, (2) identification of the relationships between chemical/physical properties of fuels at the molecular level and reaction processes, and (3) fundamentals of reactions and control of sulfur, nitrogen, and mineral components in solid fuels. Exploratory research efforts may include hazardous waste disposal, liquid fuels, or catalytic combustion of NO_x.

Working groups are being established in each of the research thrust areas. These small groups, to be composed of ACERC researchers and external participants, will provide for technical interchange and will help identify continuing research needs. Each working group will meet at least once each year.

TABLE 4 Research Projects, First Year

Thrust Area	Research Project(s)
1. Fuel characteristics and reaction mechanisms/submodels	Fundamental research on coal structure and characteristics and its relation to reaction processes (four projects)
2. Minerals, fouling, and slagging	Identify from the literature and ongoing research information and research needs for submodel (one project)
3. Pollutant formation--mechanisms/submodels	SO_x submodel with sorbants (one project)
4. Comprehensive model development	Develop generalized graphics code for use with workstation (one project)
5. Process data/model evaluation	Design- and structure-improved laboratory reactor. Make key measurements for model evaluation (two projects)
6. Exploratory areas and other projects for near-term consideration	Extension to liquid fuels; extension to hazardous wastes (one project); radiative properties

Research Projects

The heart of the Center research program will consist of about seven to nine research projects at BYU and three to four at the U of U, identified on the basis of expertise of the investigators and pertinence to the focus/subject areas. One or two outside projects from other universities having complementary strengths in combustion may also be considered. About 20 graduate students and 7 undergraduate students will be supported with ACERC funds. Table 4 identifies the first nine research projects planned for ACERC support (thrust areas 1–5). These projects have been selected based on research requirements for development of the comprehensive model and the capabilities of ACERC researchers. The projects have been reviewed by the Technical Review Committee. ACERC investigators have prepared work statements for review by the Technical Review Committee and the directorate. Research on these nine projects will begin in early fall 1986.

Computer Facilities

Access to high-speed computational facilities is vital to the accomplishment of ACERC research objectives. Plans have been developed to provide these facilities. Evaluation of various mini-supercomputers has nearly been completed, and prices on five candidate computer systems have been requested. Benchmark computations on several candidate computers have been performed using an available combustion code. Acquisition of a mini-supercomputer is planned by fall 1986. We plan to link this computer with a set of prototype workstations, which will include a microcomputer and graphics display unit. The set of workstations will serve ACERC researchers in code development. It will also provide a framework for smooth transition of this technology to industry. It is planned that industrial implementation of ACERC products will include the use of a standard workstation.

A proposal has also been submitted to the National Science Foundation (NSF) for acquisition of an NSFNET link to the NSF supercomputer network. The mini-supercomputer will be linked to this network to provide the basic computational facilities for ACERC work. The Computational Center has been designed to house the computer facilities. The new laboratory of about 4,000 sq. ft. is under construction, with completion expected by early 1987. The center will contain the mini-supercomputer and prototype workstations with microcomputer and graphics units. This new space will also include two new laboratories for characterization of fuel structures and basic fuel reaction rates.

ACADEMIC PROGRAM

Our objective is to educate students in engineering and scientific fundamentals using the systems approach in a way that will prepare them to solve a wide range of problems. Fellowship support will be provided for 4–5 graduate and 8–10 undergraduate students. A combination of 3–4 new and 20 currently available courses among six departments in four colleges at the two universities will provide a broad basis for both general and specific education in combustion-related science and engineering. At the undergraduate level, students will receive general exposure to systems, energy, and environmental engineering in the form of senior electives and a senior project; a new undergraduate program option will be established in the Chemical Engineering Department at BYU.

Graduate students will receive a more specific education in such topics as combustion science and engineering, kinetics, physical and chemical structure of solids and fuels, and process modeling and control. A graduate-level minor in combustion will be established in the Chemical Engineering Department at BYU. Selected courses, seminars, and ad hoc seminars conducted by visiting industrial lecturers at both universities will be offered to all students in a coordinated curriculum. An effort will be made to use remote circuit television effectively between the two campuses. Graduate and undergraduate participation in combustion research will be stimulated by research fellowships and assistantships. A continuing education program will also be organized to serve the needs of industrial engineers and scientists for professional development in combustion-related subjects. The academic program is to be initiated in the fall of 1987.

INDUSTRIAL RELATIONS AND TECHNOLOGY TRANSFER

Technical associates and industrial affiliates of the Center, including 19 U.S. companies and the U.S. Department of Energy, shown in Table 5, will provide additional support of ACERC activities over the next five years. Visits and interchanges of students and faculty with industrial professionals from these companies are planned. Center funds will provide half the support for a visiting industrial research fellow on a continuing basis. To promote technology transfer, an annual review and a biennial technical conference will be held on campus with presentations on advanced combustion technology from the Center and from industry. The Center will also disseminate new information through a newsletter, annual technical reports, journal publications, presentations at meetings, technical workshops on computer model use, and ACERC computer networking. Eventually, transfer of the advanced computer-aided combustion design software, together with recommendations for associated workstation hardware, will represent the dominant element of technology transfer.

TABLE 5 Technical Associates and Affiliates

Technical Associates
Advanced Fuel Research, Inc.
Babcock and Wilcox
Combustion Engineering, Inc.
Conoco, Inc.
Electric Power Research Institute
Empire State Electric Energy Research Corp.
Foster Wheeler Corp.
Gas Research Institute
Pittsburgh Energy Technology Center
Tennessee Valley Authority
Utah Power and Light Co.
Technical Affiliates
Corning Glass Forks
Eyring Research Institute
Kaiser Coal Corp.
Los Alamos National Laboratory
Questar Development Corp.
Shell Development Co.
Southern California Edison
Allison (General Motors) Corp.

NEAR-TERM ACERC PLANS

Several ACERC activities have been identified. In July 1986, a one-day workshop was held to familiarize ACERC investigators with the status and needs of advanced combustion computational methods. This workshop was intended to provide for closer coordination of planned research investigations and Center needs, and to assist investigators in preparation of acceptable work statements. A second interchange, with the Executive Advisory Council, is to be held in the fall of 1986. Completion of the new ACERC office complex is anticipated by early fall 1986, while completion of the next Computational Center and other laboratories is scheduled for early 1987. The first research projects were initiated in September 1986, and a workshop for principal investigators is planned for early October, where each will outline his or her research program and its relationship to ACERC objectives. Discussion meetings of various working groups are to be scheduled for sometime during the first year. The first campus meeting of industrial partners is planned for February 1987, prior to submission of the second-year proposal. The academic program is to start in the fall of 1987.

Engineering Design Research Center

SAROSH N. TALUKDAR AND ARTHUR W. WESTERBERG

The goal of the Engineering Design Research Center (EDRC) is to develop better, quicker design techniques for U.S. industries.

Today, a major engineering product takes years to design—about 3 for a car, 5 for a computer, and 10 for an aircraft. The time constants of the marketplace and technological development are often much shorter. As a result, products can be obsolete or uncompetitive even before they go to market.

Today's design techniques make it difficult to accommodate the concerns of multiple parties. In other words, it is difficult to design to meet, all at once, the needs of the manufacturer, the tester, the maintainer, the user, and the public at large. Instead, most of these needs must be sacrificed in order to satisfy a few.

We intend to develop techniques that will allow designs to be completed very much more quickly and to include the concerns of many more parties.

BACKGROUND

The Life Cycle of an Artifact

An *artifact* is an object that engineers create. Such an object may be material, like a car; symbolic, like a computer program; or abstract, like an algorithm or a manufacturing process.

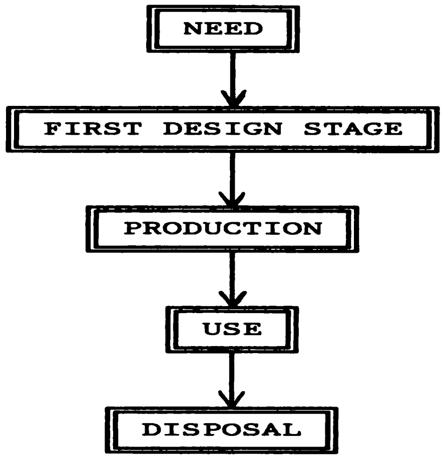


FIGURE 1 Life cycle of an artifact.

The life cycles of artifacts have five main phases, as shown in Figure 1. In the first, the need for the artifact is perceived. In the second, some of the important aspects of the artifact are designed. (As we will make clear, there are other important aspects that cannot be designed until later.) In the next phase the artifact is made; then comes a phase of use, maintenance, and modification; and finally, the artifact is decommissioned.

What Is a Design?

A design is information—specifically, the information needed to produce one or more aspects of an artifact. Under the category of *aspects* we include not only the overt form of the artifact but also all its more subtle properties, such as its reliability and quality, and all the procedures involved in its life cycle, such as the ways in which it is to be made and maintained. Some aspects that are of great interest to the Center are:

- form
- function
- manufacture
- testing
- maintenance
- reliability
- quality

- environmental impact
- safety
- liability
- disposal and recycling

Design is inherently a multistage activity. There are two reasons for designing an artifact in stages. First, it is necessary to decompose the overall design problem into subproblems of manageable size. One could, in principle, design the physical form of a material artifact and the procedures by which it is to be manufactured, all at once. However, there are usually so many different skills involved and so many different issues to consider that the only practical approach is to design the manufacturing process after the form has been established.

Second, some desired properties of an artifact invariably remain unknown until late in its life cycle. For instance, the original designers of the Taj Mahal (a marble tomb built several hundred years ago) could not possibly have anticipated the damaging effects of modern air pollution levels, and therefore could not have designed the specific modifications that are now necessary to preserve it.

The key question is: How are the decisions made in upstream design stages to be kept from thwarting downstream stages?

The activities of each stage of a design process are shown in Figure 2. One begins with specifications that come from outside or are handed down from preceding stages. Next, a *concept* must be acquired. (A concept is the skeleton of a design). The intellectual process for acquiring a concept ranges all the way from invention to reverse engineering (copying an existing artifact), and includes borrowing ideas from an existing design. The next step is to generate/synthesize the details necessary to flesh out the concept into a full-fledged design. The final step is to evaluate the design and see if it meets its specifications. The steps are executed iteratively, as indicated in Figure 2.

The steps mentioned in the preceding paragraph involve three levels of intellectual activity:

- High—creative, original, and abstract thinking of the sort used to invent new things. This level of thinking is little understood and is well beyond our capabilities to automate.
- Intermediate—qualitative reasoning that involves intelligence and judgment of the sort that can be captured in expert

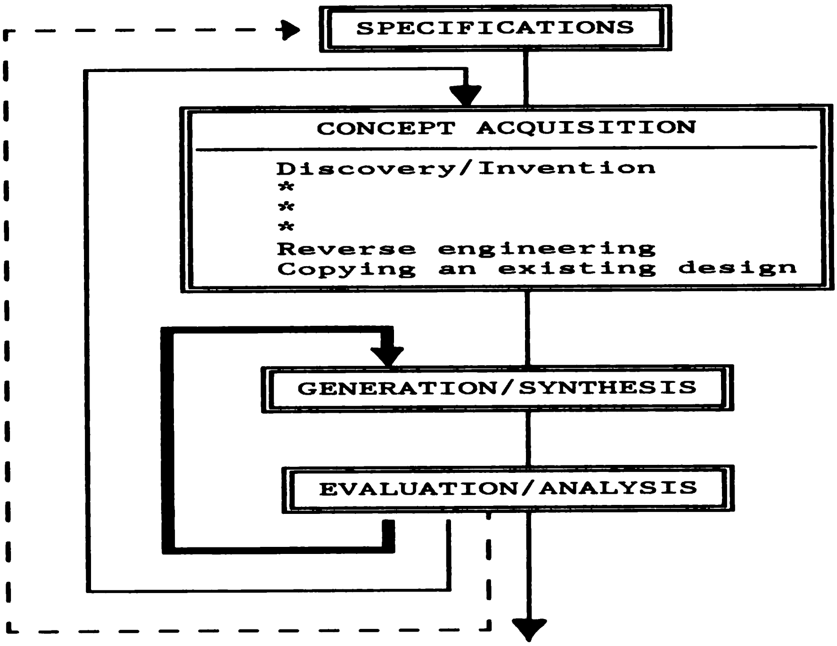


FIGURE 2 Model of a design state.

systems. Examples include managing information flows among computer-aided design (CAD) tools, managing design projects, synthesizing new systems from existing components, and evaluating designs in terms of nonquantifiable attributes like quality and safety. There are few automatic tools at this level, but the technology exists to create them.

- Low—detailed, quantitative reasoning of the sort involved in numerical algorithms for simulation and optimization. This level is well populated with tools. In fact, most existing CAD tools belong in this level.

Design knowledge is split between universities and industries. The former are active in the research of quantitative methods. But much of the knowledge used in the qualitative parts of design can be found only in industries.

Summary

- Designing is an information-intensive process.

• To design better and more quickly will require handling much more information much faster than is done today. This can only be done with more automation.

• Life cycle design is a multistage activity. To do it well, ways must be found to keep decisions made in upstream stages from thwarting downstream stages.

• There is a lack of automatic tools for the intermediate, qualitative level of design activity.

• Much of existing design knowledge is found in industries.

• The high-level, conceptual parts of design activity are not well understood.

THE CENTER'S APPROACH

A Broad, Cross-Disciplinary View

In 1974 the Design Research Center (DRC) was formed at Carnegie-Mellon University to study the common aspects of design and to develop cross-disciplinary experts. The EDRC is using these experts to help formulate policy.

The EDRC is undertaking four types of activity:

1. Planning—to use teams of industrial and academic people to examine the industrial scene and anticipate the important problems that will need solution a few years hence.
2. Methods—to develop generic approaches to solving critical, widely encountered problems.
3. Pilot-Scale Applications—to undertake short-term projects with high payoffs to serve as showcases for the Center's developments and testbeds for the ideas developed in "Methods," described above.
4. Support—to provide an outstanding environment (computer hardware and software) for research and education.

Key Research Areas

The projects in the Center are being selected to cover the following key areas:

• Life cycle design

• Tools for the intermediate level of design activity— specifically, the qualitative and generative aspects of design

- Tool integration and design environments
- Rapid prototyping
- Understanding the high, conceptual level of design

The Center will achieve high research productivity through:

- Knowledge pooling and cross-fertilization among its projects
- Selecting projects so that they can interact synergistically
- The superior research environment provided by its support activity
- Establishing and maintaining strong industrial ties

Technology Transfer

The Center will seek to achieve effective technology transfer through:

- Joint projects with industry
- Showcase projects
- Enhanced education programs

STATUS OF PROGRAMS

First-Year Projects

The following projects have either been initiated or are in advanced stages of planning.

1. *Rapid prototyping of single-board computers*. The objective of this project is to develop an automatic system that can translate arbitrary specifications for a single board computer into a working prototype in one or two days.

2. *Rapid prototyping for injection-molded parts*. The aim of this project is to design and produce prototypes of some yet-to-be-chosen class of injection-molded parts, like headlamp lenses, in a matter of days. The project is being negotiated with General Motors.

3. *Design for manufacturability of very large scale integrated chips*. This project will examine ways to take manufacturing and scheduling concerns into account in circuit design.

4. *Multistage coordination in steel making*. Steel making is a multistage process. By learning how to coordinate the stages, we intend to develop techniques for life cycle design.

5. *Synthesis methods*. This project will develop methods for synthesizing civil and chemical systems and will extend these methods to other problem areas.

6. *Tool integration/design environments*. This project will study the needs of design environments in electrical and civil engineering, and thereby develop powerful means to integrate and supervise CAD tools.

7. *Redesign of electromechanical objects for assembly*. This project will develop methods to tailor the design of an object for assembly or disassembly by robotic facilities. The projects and researchers have been carefully selected for synergistic interactions and to cover the key research areas mentioned earlier. The only area not covered is "understanding the high, conceptual level of design." A project in this area is in the preliminary planning stage.

Support and Facilities

The current complement of computers includes a Gould 9080, several Hewlett-Packard 320 workstations, several Sun workstations, and an assortment of other workstations. More equipment is on order. We are in the process of establishing a network of stations for design. An organization to maintain the computers has been set up.

Plans for renovating 7,000 sq. ft. of space are nearing completion.

The search for an assistant director, to set up and run an industrial affiliates program, is under way.

CONCLUSION

As of this time of writing, the Center has been in existence for two months and is still in a start-up phase. Significant levels of research activity should be under way by August 1986.

Engineering Research Center for Compound Semiconductor Microelectronics

GREGORY E. STILLMAN

INTRODUCTION

Background

Rapid advances in the fabrication of compound semiconductor electronic and optical devices, such as high electron mobility field effect transistors, heterojunction bipolar transistors, lasers, and photodetectors, and in the development of new fabrication techniques, make it possible to combine electronic and optical devices in a single circuit, creating a powerful new class of monolithic optoelectronic integrated circuits (OEICs) that could have a wide range of applications in both optical communication and information processing. These OEICs have the potential to be smaller, more reliable, and less expensive, with higher performance than electrically connected discrete devices. In each of the electronic and optical devices mentioned above, the performance available from simple elemental or compound semiconductors has been greatly enhanced by using multiple heteroepitaxial compound semiconductor structures, so-called artificially structured materials (ASMs), which provide special properties such as higher carrier mobility, higher injection efficiency, lower laser thresholds, and faster, more sensitive photodetectors.

The National Science Foundation (NSF) Engineering Research Center (ERC) for Compound Semiconductor Microelectronics, dedicated to research on the growth and characterization of these artificially structured compound semiconductor materials, was established at the University of Illinois at Urbana-Champaign on May 1, 1986. In recent times probably no single field has had a greater impact on the national productivity and quality of life in the United States, and the world, than has semiconductor microelectronics. Semiconductor electronics has revolutionized the infrastructure of our society, ranging from data processing to home appliances and the entertainment industry, to the medical professions. It has made possible sophisticated navigation and control for aviation and the transportation industries, it is central to the computer industry, and it is critical for our national defense. It is now on the verge of producing an information explosion through the related areas of high-speed supercomputers, optoelectronics, and lightwave technology.

The United States is now engaged in an international competition to maintain the supremacy in electronics that we have enjoyed since the invention of the bipolar transistor in 1947. The loss of this supremacy would be a more serious blow to our national productivity and security than the setbacks in the automobile and steel industries have been. Key elements in this competition are electronic materials and new concepts for future high-speed electronic systems. Preeminence in the field of advanced electronic materials is crucial in the critical areas of information, communications, computers, computation, and control. To maintain our lead there must be an increased emphasis on new materials and technologies suitable for advanced generations of computers, including high-data-rate transmission and processing techniques, and for specialized applications involving high-speed processing, optoelectronics, and radiation hardness. To achieve the desired goal of success in this international competition, an integrated interdisciplinary approach will be required, including the development of the essential concepts and techniques and the training of engineers to implement them. The program of the NSF Engineering Research Center for Compound Semiconductor Microelectronics at the University of Illinois at Urbana-Champaign has been developed, and the participants in this Center have been solicited from the interdisciplinary engineering areas to achieve these ends. Approximately 30 faculty members have expressed an interest in being associated with the

Center, while 20 industrial companies that have supported compound semiconductor research at the University of Illinois through the Physical Electronics Industrial Affiliates Program will provide the nucleus of expanded industrial support for the new Center.

Management Plan

The Center for Compound Semiconductor Microelectronics of the University of Illinois is a unit of the College of Engineering. The rank of its director is equivalent to that of department head. The director holds administrative responsibility within the university structure for the operation of central facilities and services shared by investigators associated with the Center and other users on the campus. He is responsible for space assignment and operation of the new microelectronics building. The scientific responsibility for the Center research program rests with the director.

Four committees have been established to provide advice and counsel to the director. They are the Executive Committee, the Board of Overseers, the Technical Advisory Committee, and the Cooperative Research Committee.

RESEARCH PLAN

Areas of Emphasis

A particular area of importance for the success of the future electronics industry of the United States is high-speed digital systems. In present high-speed systems conventional interconnection and switching technologies are proving to be inadequate for both silicon VHSIC/VLSI (very high speed integrated circuit/very large scale integrated circuit) and gallium arsenide (GaAs) integrated circuits. The inherent capabilities of high-speed silicon circuits cannot be utilized because of the input/output limitations. These problems are even more severe for the high-speed GaAs digital integrated circuits that are currently under development. While the development of both silicon VHSIC/VLSI and GaAs integrated circuits has been progressing, there have also been tremendous advances in the capabilities of GaAs-based optoelectronic devices using quantum wells and other multiple-layer heterostructures. The demands for increased performance of interconnects and the development of efficient, very low threshold semiconductor lasers and high-speed GaAs-based electronics combine to make the re-examination of optical interconnects for digital integrated circuits and systems very promising. Thus, one focus of the research of the Center for Compound Semiconductor Microelectronics will be the development of new concepts, materials, devices, and systems that will help to eliminate the interconnection bottlenecks that are beginning to limit the performance of high-speed digital systems.

Seven different research areas have been identified as essential for successful realization of an optically interconnected high-speed digital system such as a supercomputer. These areas, which will form the initial core research program of the Center for Compound Semiconductor Microelectronics, are (1) systems design and analysis, (2) transmission media, (3) optical and electronic devices, (4) processing and fabrication technology, (5) semiconductor device theory, (6) electronic materials, and (7) materials characterization. The research staff of the Center is divided into closely collaborating groups to meet the challenges in these research areas.

Research Groups

Seven different research groups have been established to address the areas important to the technological goals of the Center. The aims of these research groups are as follows.

I. *Theory Group*. This group concentrates on analysis of the optical and electrical properties of compound semiconductors and of the special properties that can be obtained through the use of artificially structured materials.

II. *Systems Design Group*. The focus of this group is on the potential advantages of optical interconnects in digital systems and on investigation of the architectural and system performance implications of optical interconnects.

III. *Materials Group*. This group studies the growth of multiheterostructure compound semiconductor artificially structured materials using molecular beam epitaxy (MBE), gas and metalorganic source MBE, and MOCVD (metalorganic crystal vapor deposition) growth techniques.

IV. *Materials Characterization*. For many device applications, high-purity materials are required to obtain the desired performance of heterostructure devices. The purpose of this group is to study residual impurities and the sources of these impurities for the different epitaxial growth techniques. The influence of different growth parameters on impurity incorporation is investigated using electrical and optical techniques.

V. *Processing and Fabrication Technology.* The impurity-induced layer disordering of multiple thin heterostructure layers, recently discovered by Holonyak at the University of Illinois, is one of the major areas studied by this group (Holonyak et al., 1981; Laidig et al., 1981). Other related areas include electron beam lithography, ion-implantation, rapid thermal annealing, reactive ion etching, plasma etching, and other dry processing techniques.

VI. *Optical and Electronic Devices Group.* This group studies the fabrication and characterization of high-speed optical and electronic devices for optoelectronic integrated circuits and optical interconnects.

VII. *Transmission Media Group.* This group addresses the problems of transmitting and switching optical signals that are important for making high-speed digital optical interconnects.

Laboratory Facilities

Four experimental facilities will be established in the Center for Compound Semiconductor Microelectronics to support the direct needs of the core research groups. They include (1) facility for artificially structured materials, (2) facility for ultra-high purity semiconductor analysis, (3) facility for sub-micron fabrication, and (4) facility for ultra-high speed measurements. These facilities will also play an important role in our interactions with our industrial partners. Staff members will collaborate with equipment manufacturers in the development of new equipment and with suppliers of metalorganics, gases, and other semiconductor source materials in developing new purification techniques and characterization methods. Sophisticated facilities of this type are possible at the university only in the context of a large-scale laboratory such as the Engineering Research Center.

Student Involvement

The principal objective of the educational component of the Center for Compound Semiconductor Microelectronics is to train the undergraduate and graduate students who will contribute to development of the electronic systems of the twenty-first century.

Outstanding undergraduate students will be exposed to actual industrial engineering and research projects, working with graduate students and industrial researchers in residence. It is hoped that this exposure will encourage them to pursue a graduate education. Graduate students who participate will receive a broad interdisciplinary perspective, in addition to the foundation provided by their basic curriculum.

An additional feature of the educational program is the establishment of a summer internship for students beginning their senior year. The purpose of this program is to introduce them to research at a critical time in their educational program and to encourage them to consider a graduate engineering education.

INDUSTRY INVOLVEMENT

The Center is dedicated to establishing a strong relationship with industry, working exclusively with companies incorporated in the United States. The industrial partners will play an active role in Center activities, giving advice on policy decisions, having access to patented inventions, serving on committees, directing coordinated research participation, and training and educating personnel. Emphasis will be placed on transfer of the Center's research results to the industrial partners. A close interaction will also ensure that the research directions of the Center support the needs of our industrial partners. Some industrial participants will be associate or affiliate members. The role of associate members will be that of an observer; they will receive information by such technology transfer mechanisms as the annual research meetings and workshops, technical reports, and papers.

Industrial Coordinated Research Committee

A novel feature of the Center is the Industrial Coordinated Research Program. This program is an experiment in university-industry relations, which has as its goal the coordination of parallel research and development efforts in industry and the Center. To accomplish this, a program will be initiated in which the university and industry work together on mutually defined research projects of interest to both groups. The results of their research will be made available to all participating corporations, and will subsequently be made public through normal scientific and engineering publications. A coordinated research committee will be established to explore and define research problems that are of interest to both parties. The intent is to provide an open, neutral, and scholarly environment that will encourage the sharing and delegation of research between industrial groups and the Center.

Corporate staff members will also participate in the research of the Center. For current employees the residence program will resemble a sabbatical, while for newly hired personnel it will be postdoctoral in nature, permitting graduates from any institution to acquire experience in the Center.

Information Dissemination

In addition to publications in scholarly journals, information will be transmitted to interested communities by virtue of the resident's program (educators-in-residence and researchers-in- residence) and through the existence of a public videotape and personal computer diskette library, supplemented by faculty visits to various industrial sites. An electronic bulletin board will be created to announce current events, publications, theses, and news briefs associated with the Center. It will also be used to communicate research problems and results between the Center and its industrial supporters. If needed, topical workshops, seminars, and short courses will be considered.

REFERENCES

Holonyak, N., Jr., W. D. Laidig, M. D. Camras, J. J. Coldman, and P. D. Dapkus. 1981. Applied Physics Letter 39:102.

Laidig, W. D., N. Holonyak, Jr., M. D. Camras, K. Hess, J. J. Coldman, P.D. Dapkus, and J. Bardeen. 1981. Applied Physics Letter 38:776.

Center for Advanced Technology for Large Structural Systems

JOHN W. FISHER AND ALAN W. PENSE

INTRODUCTION

Background

The Center for Advanced Technology for Large Structural Systems (ATLSS) was established at Lehigh University on May 1, 1986. The ATLSS Center will provide innovative, focused research and state-of-the-art testing facilities to modernize the structures-related industries and to help these industries prepare for the twenty-first century.

The design and construction of large structural systems for transportation, industry, infrastructure renewal, and power resource utilization are vital to the U.S. economy. They are important in both the domestic and the international markets. Construction-related goods and services make up approximately 10 percent of the U.S. gross national product. Overseas revenues received by U.S-based construction engineering firms comprise about 10 percent of total U.S. exports. American designers and builders bring multibillion dollar revenues to the United States, according to a recent study conducted by Price-Waterhouse Co., Inc. (1985), for the International Engineering and Construction Industries Council. Reductions in these services could result in enormous losses to the U.S. economy. According to the study, every $1 billion in direct U.S. revenues received by exporting construction services generates $1.27 billion in additional domestic revenues and some 24,000 jobs for U.S. engineers, architects, and constructors.

Statistics for the international design and fabrication markets for the years 1980–1984 were recently published in *Engineering News Record* (1985a, 1985b) and are shown in Figure 1. A significant decline in the share of the international market going to U.S. construction firms occurred over this period, with the United States dropping from about 45 percent in 1980 to 38 percent in 1984. Top U.S. design firms also lost ground slightly in terms of market share, falling from 31 percent in 1980 to under 30 percent in 1984. Foreign competition is keen; the charts show that some countries—notably Japan—have steadily increased their fraction of the world market.

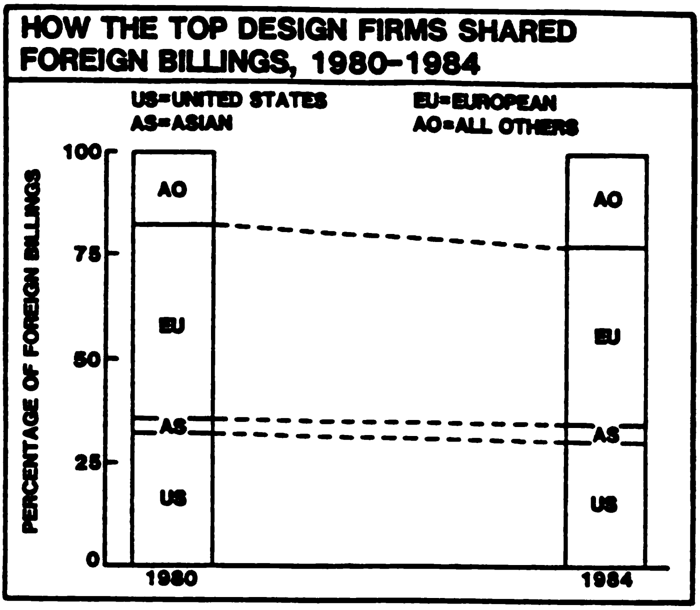
At the same time that U.S. firms are losing place in international markets, foreign design and construction firms are doing more business in this country. This fact was reported in the same *Engineering News Record* survey cited above (1985b). In 1984, the United States was a large growth market for foreign contractors. Half of the Japanese firms listed among the top 250 contractors in the world were awarded contracts in the United States in 1984, about twice the number obtained in 1983. If the United States is to hold its place in the international construction market, the large-scale structures industry must move rapidly ahead in technology.

Technological Developments Facing Construction

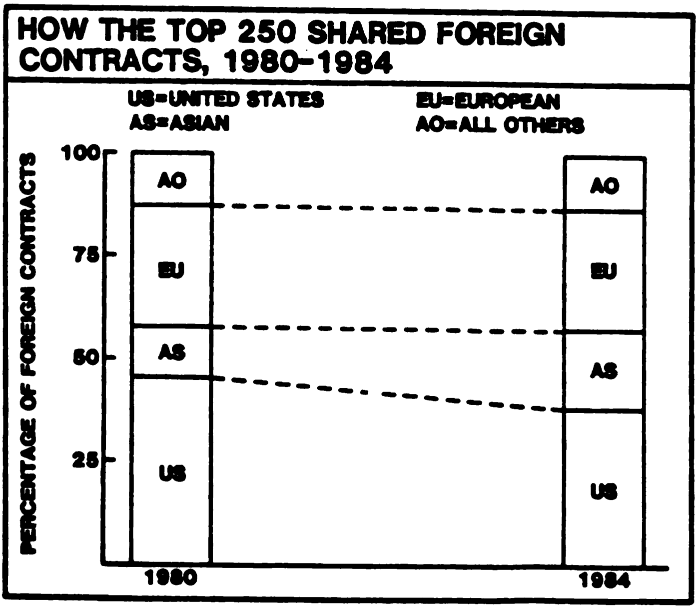
The structures-related industries face major technological developments that will significantly affect these industries into the twenty-first century. High-technology techniques and products will revolutionize design, fabrication, and life cycle monitoring and protection.

Five major technological developments can be predicted with confidence:

1. *New and better design concepts* will be possible because of better analysis methods for structures, improved knowledge and selection of materials, and better understanding of design rules. New designs will use materials more efficiently, be easier and faster to construct, and be more economical over the life



DESIGN FIRMS



CONSTRUCTION FIRMS

FIGURE 1 Nationalities of the top design and construction firms, 1980–1984 (*Engineering News Record*, 1985b).

cycle. Computer-prepared drawings, created in the design phase, will be carried through into the fabrication and manufacturing phases. Expert systems analysis will speed up both design and fabrication and will greatly reduce the potential for costly human error.

2. *New computer tools* to integrate design, fabrication, construction, safety, and monitoring, both during and after construction, will be available and will be extensively used. Project management will be almost entirely computerized. Automatic sensors will provide the data required for structural monitoring. The influences of on-site changes in design concept will be identified immediately and their consequences for costs, safety, and long-term reliability will be recognized. Necessary design changes will be more readily undertaken because the impact of such changes will be quickly determined and alternative scenarios tested.

3. *High-strength, high-value materials* will characterize construction. A greater variety of materials will be used, including hybrids of metals, concrete, polymers, and ceramics. High-strength materials will be utilized to decrease weight, and composites of various types will provide more opportunities for prefabricated and modular construction.

4. *Robotics and automation* will be standard features in construction. Most fabrication will be done in the shop, with little done on site. Shop prefabrication will permit greater use of modular components of concrete, steel, and composite sections of highly efficient design. Site work will be characterized by automated materials arrival and handling, computer-managed inventory controls, and efficient erection sequences. The entire process will be less labor-intensive and will rely on sophisticated computer software to help control the flow of materials and the application of skilled personnel with the highest efficiency and minimum cost. Application of robotics to construction will also reduce the need for physically demanding and dangerous labor tasks.

5. *New sensors, coatings, and protective systems* will be designed and fabricated into the structure. Inexpensive, on-line monitoring devices will be built-in and will provide an early warning of threats to protective coatings or structural integrity. Life cycle engineering will be emphasized, leading to optimal use of high-value materials, reduced maintenance and structural renewal costs, and extended reliability and service life.

Underlying these developments will be a much greater utilization of computer technology and knowledge-based expert systems. Some software has already been developed for construction, design, and management, but substantial improvements will be necessary. Computer technology will be especially needed in the interfaces between the separate activities of the structures-related industries. This need is illustrated in Figure 2, which sketches the principal separate activities going into large-scale construction. Each activity—design, construction, and operation—has a distinct knowledge base. Research and development can contribute to all three by extending the knowledge base necessary for improvements in design, fabrication, construction, and operation.

Figure 2 also depicts the interface between each of these activities. In many cases the interface currently limits the flow of information and the transfer of improvements in the construction industry. Computer technology will make it possible to reduce the interface constraint, leading to a more integrated engineering of structural systems. Better integration will result, for example, in effective design that considers not only the functional aspects of a structure but also the labor, time, and resources required for fabrication, construction, and operation. As these interfaces are improved, engineers performing the different activities will be better able to communicate with one another. That will strengthen each activity, reduce overall costs, and increase effectiveness. Although research engineers can succeed in discovering improvements in design, fabrication, construction, and operation, they often have

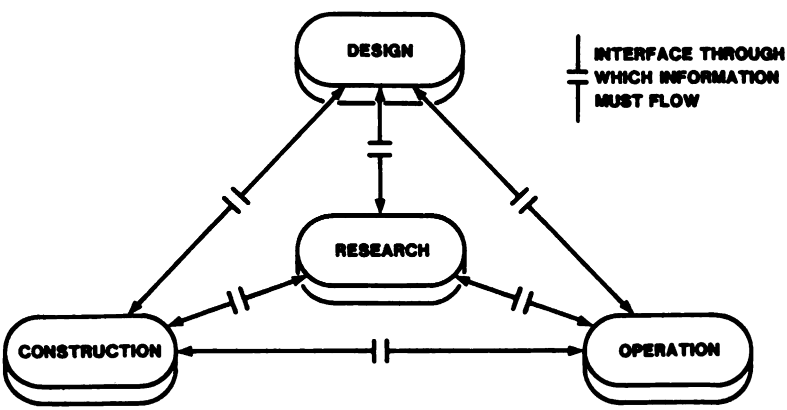


FIGURE 2 Activities to be integrated.

difficulty in communicating these discoveries across the interfaces to the practicing engineers who can benefit from them. Thus, computer data bases and other techniques to increase information flow across these interfaces will be a vital part of the work of the Center.

THE RESEARCH PROGRAM

The research program for the Center consists of three thrust areas: advances in design concepts, innovation in fabrication and construction, and in-service monitoring and protection. The three research thrusts are important to three different subsets of the structures-related industries. This provides a way to attract a range of industries to participate in the Center. Over the long term, however, the Center will catalyze the effective integration of most segments of the construction industry. Designers, fabricators, suppliers, builders, and owners will be brought together to work toward the common goal of providing more effective, efficient, and reliable systems. The Japanese have already done much to integrate their structural industries, thereby demonstrating that integration is feasible. The United States cannot afford to continue lagging behind.

Advances in design concepts addresses the need to improve upon the traditional rules, methods, and materials for designing structures. Advanced design must utilize a wide range of metals, polymers, ceramics, and composites. The design of connections between components, now an expensive part of construction, must be simplified. Connections of prefabricated components will also require new joining concepts. Advanced computer-aided design tools and knowledge-based expert systems will need to be developed and used to improve both the design process and the resulting structures. Consideration will also be given to structural systems that have components that can be readily replaced as they deteriorate and wear out.

Innovation in fabrication and construction addresses the need to modernize current construction practices that are inefficient and time/labor-intensive. Research will be conducted on how automation and robotics can be introduced where feasible. The Center will facilitate designs that reduce fabrication steps, increase structural commonality and modularity, and improve the sequencing of construction operations. Connection technology, important in design research, will also be a priority here. This thrust will investigate new materials of better fabricability and better uses of traditional materials, such as prestressed concrete. Research will improve the integration and control of site and shop operations, so that the whole fabrication process can be shortened with resulting cost savings. Sophisticated computer software will be developed to manage the complex set of construction operations.

In-service monitoring and protection, the third thrust, explores how modern technologies can increase structural reliability and longevity. Research will investigate how monitoring provisions can be introduced early into the design and how monitoring can be an integral part of the construction process, not a separate afterthought. The scope of the research includes in situ sensors that can be built into the structure, remote and automatic recording of data, and on-line data evaluation. Moreover, this thrust goes beyond sensors and monitoring; it also includes structural protection to resist gradual deterioration by corrosion and weathering. Improved nondestructive techniques to measure hidden deterioration, new protective coatings, and better application methods will receive special emphasis.

Each thrust area draws upon the knowledge base of the relevant disciplines including structural design, materials engineering, manufacturing processes, computer technology, and chemistry. As shown in Figure 3, the five disciplines and the three thrust areas have a matrix relationship. Each thrust area will utilize each discipline, but some areas will draw more heavily on particular disciplines than on others.

The structural design discipline will bring to the research program expertise in the important factors affecting design, performance, reliability, and cost. This discipline will enable research into improved design concepts, shapes, and connections for new structures and into the alternatives for the redesign and rehabilitation of older, deteriorating structures. Materials engineering will contribute to the identification, characterization, and selection of materials to meet design and manufacturing requirements. This discipline will do research not only on the traditional structural materials, steel and concrete, but also on newer materials which offer improved strength, joinability, toughness, and environmental resistance. Expertise in manufacturing processes, which includes the disciplines of industrial and mechanical engineering, will be

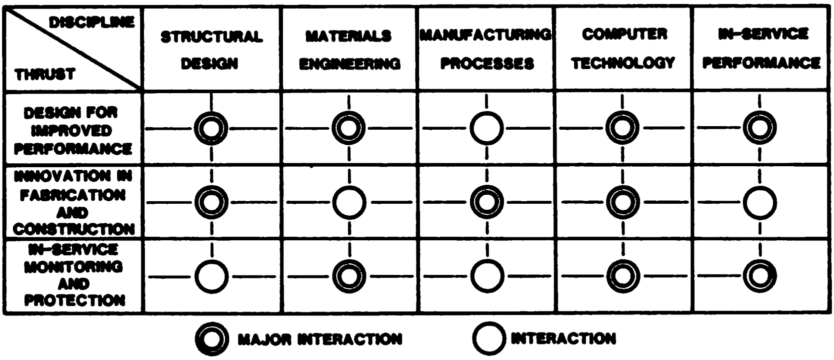


FIGURE 3 **Thrusts and disciplines involved in the Center.**

required for research on fabrication and construction, both in the shop and in the field. This expertise will be valuable for developing advanced fabrication techniques to increase automation, improve reliability, and reduce the high cost of construction labor. Computer scientists and engineers will bring an extensive knowledge of computer technology to much of the Center's research. This discipline will play a major role in the development of expert systems, computer design tools, the computerized test facility, robotics and automation, and sensor research. Chemistry will be an essential discipline for research into corrosion processes, surface preparation, coatings, sensors, composites, polymers, and other materials. Other disciplines will be drawn upon as needed to perform the Center's research. For example, electrical engineering and physics will be needed for research on nondestructive testing and remote data acquisition.

ORGANIZATION AND MANAGEMENT

Figure 4 shows the organization of the Center and its relationship to the Lehigh University organization.

Twenty-four faculty members of the Lehigh University College of Engineering and Physical Science are participating in the ATLSS Center activities. These faculty members will be drawn from the Departments of Civil Engineering, Metallurgy and Materials Engineering, Mechanical Engineering and Mechanics, Computer Science and Electrical Engineering, Industrial Engineering, and Chemistry. In addition, several faculty from the College of

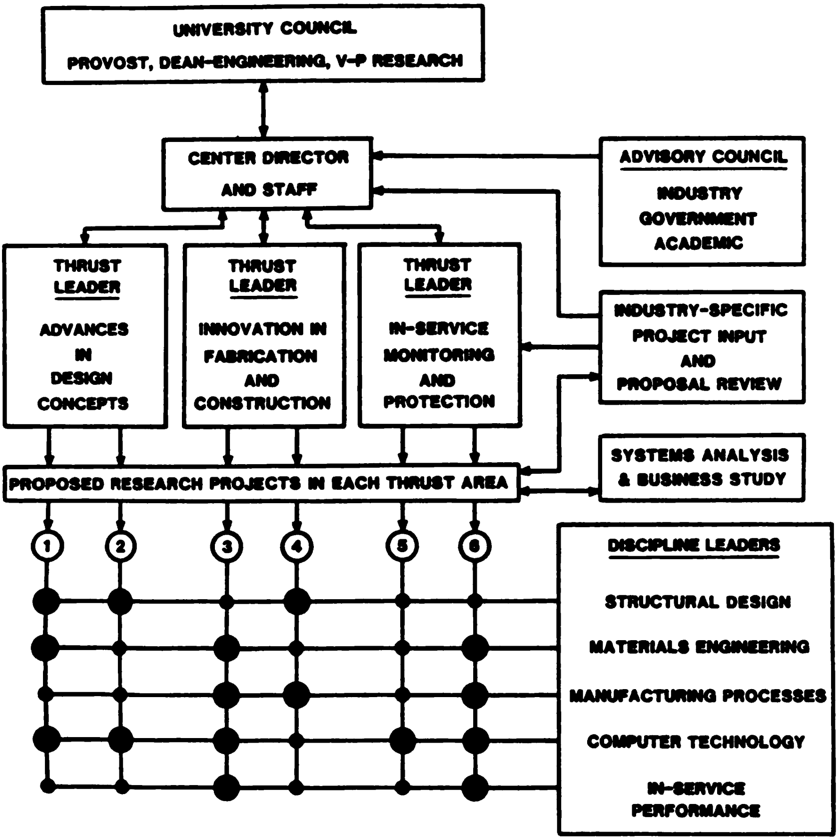


FIGURE 4 Center management structure.

Business and Economics will be participating in evaluating the economic impact of research, examining the cost and capital requirements of projects, and assessing the development of evolving technology. Faculty from the Business College will also work with engineering faculty and students on construction systems and management studies.

Faculty performing research in the Center will be associated with projects in the various thrust areas. Although identified academically with specific disciplines, the faculty will be most strongly aligned in the thrust areas so as to encourage cross-cutting approaches to the research. Both thrust areas and discipline areas will have faculty who will be key leaders in research. However, it is the thrust area leader who will serve as program manager and who will thus be responsible for developing problem-oriented, cross-cutting research. As such, the thrust area and discipline leaders, with industry input, will assist the Center director and his staff in identifying and formulating appropriate research topics that will advance the relevant thrust.

Guidance for the research program will be provided at two levels, as shown in Figure 4. At the Center level, an Advisory Committee has been established to assist in selection of general topic areas and to evaluate the present and future direction of the Center. This committee currently has 13 members and will meet once or twice annually. At the project level, there will be industry, government, and academic advisory personnel on project committees that will deal with the technical issues. These individuals will be drawn from fabricators, suppliers, designers, code representatives, and others.

The main research thrusts for the Center extend over a wide range of individual research topics and general areas. It is anticipated that these themes will serve as guides for the initial years of operation. In the longer term, however, new themes may need to be added. The overall focus of research in the Center is of critical importance, so that these decisions should be undertaken only in the context of the national mission, and only with the participation of each element of the Center's support base.

CRUCIAL NEW FACILITY

The Large-Scale Multidirectional Loading Facility, which will be part of the Center, will provide an experimental capability that does not now exist in this country at the large scale required. This facility will include two intersecting reaction walls at least 35 ft. high and will have appropriate tiedowns in the test floor to permit three-dimensional loading. Multidirectional facilities available in Texas and Michigan do not have the size and capability needed. The recently constructed large-scale reaction walls at the University of California, San Diego (*Engineering News Record*, 1985c), and at the National Bureau of Standards (*Civil Engineering*, 1985) provide single reaction wall capability but not the multidirectional capability that will be provided at the ATLSS Center. In fact, only three free-world countries (Japan, England, and Norway) now enjoy such a large-scale facility; in all three cases the facility was constructed with governmental support and leadership. The lack of such a facility in the United States is jeopardizing the traditional engineering strength of U.S. firms offering services abroad.

The facility will be used in many of the Center's research projects. It is needed to perform static and cyclic multidirectional loading tests on very large connections, assemblages, and structures. These tests are essential for developing a better understanding of large-scale structural behavior. Several major structural failures are attributed to designs based on small-scale test results which provided erroneous resistance levels when extrapolated to large structures.

The Large-Scale Multidirectional Loading Facility is also needed to improve our ability to deal with infrastructure problems. In particular, rehabilitation of existing, older structures can be improved through greater use of larger prefabricated components. The facility will provide a better understanding of large-scale beams, columns, slabs, floors, and other components. Of course, these benefits will be realized in new design concepts as well as in the redesign of existing structures. The result will be greater human safety, higher productivity, improved use of resources, and more reliable structural systems.

The new multidirectional loading facility will become a unique state and national testing facility and resource for large-scale tests. The Center will make this facility available to industry, government, and other university research and development personnel, thus providing them with a capability not now available in the United States.

EDUCATION AND TECHNOLOGY TRANSFER

At the time of admission to graduate school, the students who enter this program will be identified as Center research scholars and will tailor their course work and research programs accordingly. Although degrees will be granted by the individual departments, it is current Lehigh policy for the M.S. and Ph.D. programs to permit extensive out-of-major-department course work. Abundant successful precedent may be found in other interdisciplinary research centers at Lehigh; they support departmental degree programs for students committed to cross-disciplinary research projects in the research centers. Each scholar, under the guidance of his or her adviser, will select courses outside the normal discipline in keeping with the nature of the student's research and extending the student in one or more new areas.

In addition, three major new educational activities will be included in the Center. They include new structures-related courses, case study teams with industry participation, and computer-simulated construction projects. Industry personnel will be involved in a number of graduate educational programs. This will likely include participation in team-teaching courses where expertise is not available on the Lehigh faculty, and participation on the case study teams.

The program will also encourage the sharing of research equipment and office space by graduate and undergraduate students from the different disciplines. To the greatest extent practicable, the graduate research assistants on a particular project will come from different academic backgrounds. Such collaboration has been a common practice at Lehigh as far back as the late 1940s—e.g., civil engineers and metallurgists in fracture of pressure vessel steels; civil engineers and electrical engineers in vibration of stranded cable; industrial engineers, civil engineers, and mechanical engineers in tall steel buildings; and metallurgists and civil engineers in fatigue of bridge members.

Undergraduate students will join in the work of this Center as student assistants and through "special topics" courses, for which they will receive course credits.

Lehigh has long been associated with other educational institutions in joint programs. Three other institutions will participate in the engineering research and education programs of the Center. They are Lafayette College, Bucknell University, and Villanova University, all located in Pennsylvania. These schools have agreed to share students and research expertise or facilities with the Lehigh Center.

Transfer of advanced technology from the research laboratory to industry represents a major challenge to improving product quality and enhancing U.S. competitiveness. For example, recent surveys by the National Bureau of Standards have shown that better technology transfer can save a substantial portion of the funds now going to solve problems involving corrosion and fracture. Technology transfer can also contribute to the rehabilitation and maintenance of existing structures. Examples are life extension by retrofitting problem details, improved corrosion protection techniques for deteriorated structures, better monitoring of components so that end-of-life predictions are more accurate, and early identification of generic design problems with appropriate corrections for these conditions.

Information dissemination and technology transfer will be important functions of the new Center. The technology transfer program will help structures-related industries to design and fabricate structures that are more reliable, more innovative in design, less resource-consuming, simpler and less costly to produce, and more dependable. An important benefit will be the rapid application to practice of the new concepts resulting from the Center's research.

REFERENCES

Civil Engineering. 1985. NBS to test bridges for earthquakes. 55(1):18.

Engineering News Record. 1985a. Top international contractors, builders rate foreign markets. 215(3):54–55.

Engineering News Record. 1985b. Top international contractors, foreign contracts slump further. 215(3):34–53.

Engineering News Record. 1985c. Full-scale structures to be tested in new lab. (May 9):13.

Price Waterhouse Co., Inc. 1985. Study performed for the International Engineering and Construction Industries Council. American Society of Civil Engineers. Civil Engineering, 1985.

Engineering Research Center for Net Shape Manufacturing

TAYLAN ALTAN

INTRODUCTION

Background

The College of Engineering of The Ohio State University (OSU) was selected by the National Science Foundation to establish one of the five new Engineering Research Centers started in 1986. The focus of this Center is net shape manufacturing, with emphasis on cost-effective manufacturing of discrete parts. The research will concentrate on manufacturing from engineering materials to finish or near-finish dimensions via (a) melt processing (casting, injection molding), (b) shaping from powder, (c) forming from sheet, and (d) forming from billet.

In a net shape manufacturing process, a given material (usually shapeless or of a simple geometry) is transformed directly into a useful part. The resulting part has a relatively complex geometry with well-defined shape, size, geometry and tolerances, appearance, and properties. The desired geometry is "stored" in the tools, dies, or molds and imparted onto the material with or without pressure through the tool/material interface.

Net shape manufacturing technology has great potential to conserve resources (material, energy, time, human resources) and to reduce overall manufacturing costs. There is a great need for applied research in this specific technology in order to maintain the nation's technological leadership and international competitiveness in manufacturing. The technology is multidisciplinary, represents a microcosm of nearly all manufacturing activities, can greatly benefit from the wide application of CAD/CAM/CAE (computer-aided design/computer-aided manufacturing/computer-aided engineering) and is well-suited for joint industry-university cooperation.

The Center will help industry to:

- reduce the development time for new processes by eliminating trial and error through process simulation and integration;
- predict material flow and eliminate defects to increase product quality and consistency; and
- improve dimensional tolerances and increase achievable shape complexity to make net shape manufacturing more cost-effective for wider use.

Focus of the Center

The focus of the Center has been selected carefully with the following considerations.

1. In all net shape manufacturing processes as defined here, the part geometry is the common thread. The technology of die/mold design and manufacturing is common to all processes that are being considered.
2. The physics of the net shape manufacturing processes have a lot in common. For example, in all such processes we have mass flow in solid, liquid, or powder form; therefore, we must understand material behavior under processing conditions. Heat transfer and material/die interface problems are similar. Because of these similarities, extensive cross-fertilization is expected among various research tasks, teams, and projects.
3. Research and development in net shape processing have been neglected. When discussing manufacturing, most of us tend to think in terms of machining, systems, and automated handling. We seem to forget that if we do not put the excess material on a part in the first place, we do not have to machine it off. Net shape manufacturing processes are highly experience-based. Tool and die making and process development are an art rather than a science.

We need to understand the physics of these processes to make them more cost-effective and to achieve the benefits they offer. We must replace art with science and engineering. This is especially true in manufacturing from new materials such as high-temperature alloys, composites, and ceramics.

RESEARCH PROGRAM

To achieve the Center's goals, the research program will (a) integrate part design, material selection, and the manufacturing process; (b) have strong industry input in selecting, conducting, and monitoring the individual programs; and (c) consider shaping processes in a generic sense as a system comprising input material; tooling; tool/material interface; mechanics of shape change; machinery and handling devices; and the product geometry, tolerances, and properties.

The research direction of the Center is guided by the premise that, in the future, design and manufacturing will be truly integrated. As illustrated in Figure 1 and based on functional requirements, the geometry (shape, size, surface finish, and tolerances) and the material (composition and heat treatment) of a part are selected at the design stage. The decisions made at this stage also determine the overall manufacturing, maintenance, and support costs associated with the specific product. Consequently, the designer uses the part geometry as the common link and starts with an alternative design using appropriate software for structural, heat transfer, and fluid flow analysis. The designer then explores several design and manufacturing alternatives before selecting one of the design alternatives. The application of the design and manufacturing integration to net shape manufacturing is illustrated in Figure 2. The key research issues of this approach are:

1. *Design for producibility by net shape manufacturing and preliminary design of dies and molds.* These are nonalgorithmic activities and can benefit from the expert systems methodology by storing existing design experience in a systematic manner.

2. *Computer modeling of net shape manufacturing processes.* Development of such models requires (a) the determination of the behavior of the materials under processing conditions, (b) an understanding of phenomena at the tool/material interface (including friction and heat transfer), and (c) the mathematical modeling of the mechanism of shape and property change.

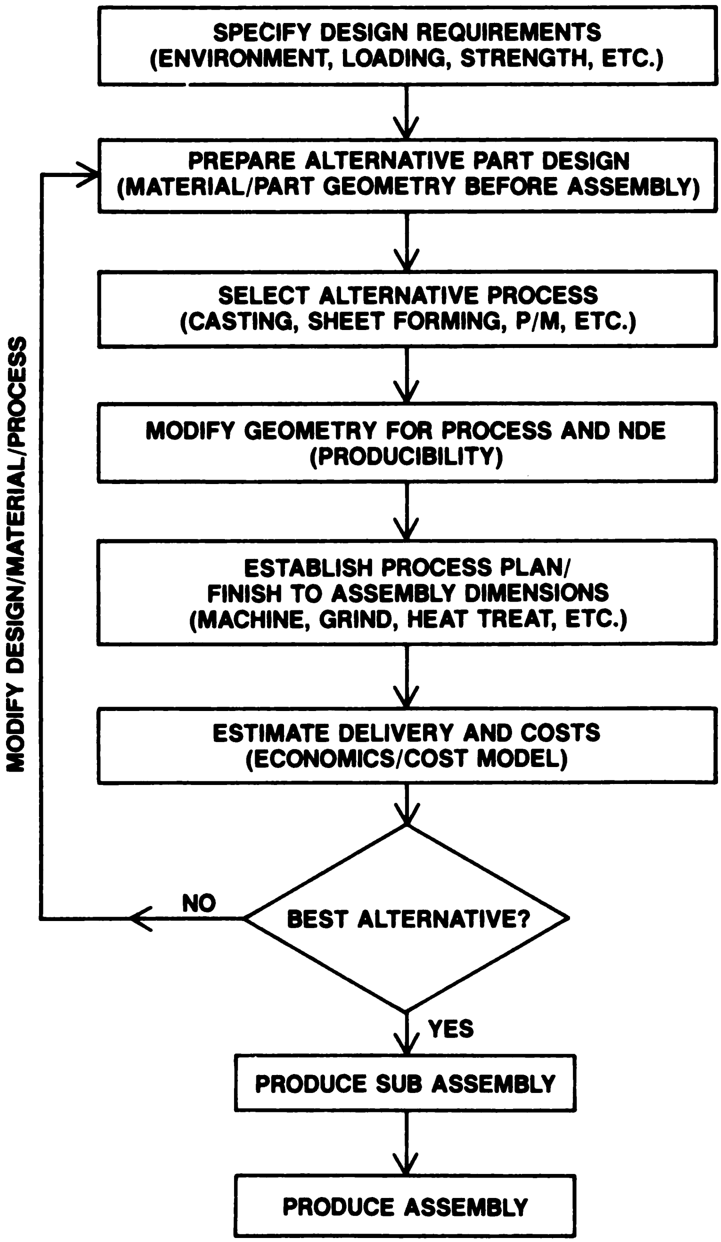


FIGURE 1 **The future of manufacturing (integration of design and manufacturing).**

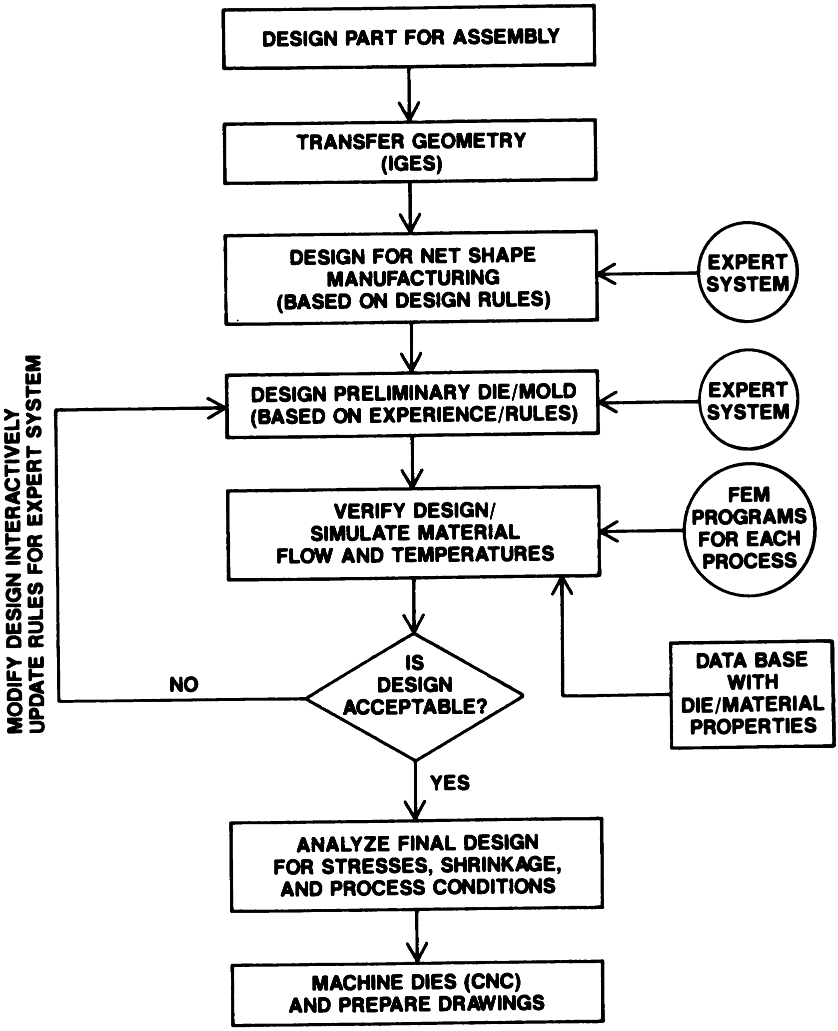


FIGURE 2 Outline of a demonstration project.

3. *Development of novel concepts for tooling, machines, and material handling.* These include (a) tool and die design and manufacture; (b) machinery, handling devices, and automation; and (c) plant layout and management-related problems.

In order to consider the foregoing issues in a systematic manner and to guide the overall research direction of the Center, several demonstration or validation projects are planned. Following the outline given in Figure 2, these will be conducted in close cooperation with the industrial members of the Center in each major research area—i.e., forming from sheet, forming from billet, melt processing, and powder consolidation. For this purpose, several prototype products will be selected and the optimal manufacturing process sequences will be established and implemented from design concept through prototype manufacture. These validation projects will utilize the results of the Center's research and will serve to refocus the Center's research program.

EDUCATION

At the undergraduate level, the Center will support the ongoing programs in competitive honors research and cooperative education. In addition, the Center will introduce a new summer internship program for undergraduates. In this program, selected students will work, at competitive wages, with faculty and Ph.D. students on a well-defined portion of a Center project. At the graduate level, the Center will support M.S. and Ph.D. research on subjects related to the Center's focus. The master's students will be enrolled in OSU's Manufacturing Systems and Engineering Program, which is an interdisciplinary program having the participation of seven academic departments. To attract more U.S.-resident graduate students, industry fellowships will augment the usual graduate stipends. To support professional development in cooperation with OSU's existing Continuing Education Program, new courses on various aspects of net shape manufacturing will be offered to the general public. This will be in addition to the usual seminars, workshops, and review meetings that will be part of the research programs. In addition, special arrangements have been made to include Ohio's state-supported colleges in the Center's activities.

INDUSTRIAL PARTICIPATION

The success of the Center will depend upon industry participation. This participation will involve a contribution of $25,000 per year for full members or $2,000 per year for affiliate members with less than 500 employees, as well as active involvement in the Center's activities. That involvement can take many forms: memberships in advisory boards and project teams, advisers/monitors to projects, instructors/researchers in residence, instructors for short courses, etc. In addition, it is hoped that companies will get involved with students and faculty through cooperative programs, term appointments to faculty, and use of company-owned equipment, and that they will contribute to the graduate fellowship program for U.S. residents mentioned earlier ($15,000 for each individual corporate-named fellowship). Thus, the participation of industry in the Center's activities will be in the form of "cooperation" and "partnership," not just in the form of financial support.

This degree of participation will involve a two-way communication between the Center and industry. The Center will attempt to develop new knowledge and technology, while industry will assist the Center staff in identifying high-payoff research topics. Technology transfer activities will involve (a) residence of a faculty member in industry and residence of industry representatives at the Center, (b) industry participation in project selection and performance monitoring, and (c) dissemination of results through reports, seminars, videos, etc.

CENTER MANAGEMENT

The offices of the Center are centrally located on the main campus of The Ohio State University. The Center utilizes the computer and experimental facilities of the various departments of the College of Engineering, the Battelle Memorial Institute, and member companies. The director of the Center reports to the dean of the College of Engineering and is advised by the Administrative, Research, and Educational Advisory Boards of the Center. These boards consist of representatives of member companies and university faculty.

In selecting projects for funding, the Center invites proposals from faculty and industry. The project budgets are expected to include appropriate funds for participation in conferences, and the project plans must consider the faculty members' interest in publications. These features help to ensure that a large number of qualified faculty are interested in participating in the Center's activities. Proposals are reviewed by the Research Advisory Board or its representatives. The criteria for funding include: (1) significance, relevance, and quality of the proposed work; (2) qualifications of the investigators and cross-disciplinary aspects of the research team; (3) probability of success; (4) potential impact of project results upon manufacturing cost, quality, and flexibility; (5) level of student participation; and (6) plans for industry participation and technology transfer. Typical projects are planned and conducted by a team of faculty and industry representatives. The progress of each funded project will be monitored by an industry representative assigned by the Research Advisory Board.

PROGRESS AND IMMEDIATE PLANS

The ERC for Net Shape Manufacturing was officially established on May 1, 1986. As of September 1986, the following preliminary steps have been carried out.

1. An Interim Advisory Board has been established. The membership of this Board consists of several industrial supporters and faculty members. It is expected that within the next six months this board will have been replaced by the management structure outlined earlier.
2. Interim operational guidelines have been established. As approved by the Interim Advisory Board, the membership fee for full member companies will be $25,000 per year while the affiliate members, consisting of companies with less than 500 employees, will contribute $2,000 per year. While affiliate members may be elected to the Advisory Boards, they will not have a vote for electing members to these boards.
3. Start-up procedures have been established. For this purpose, 15 research initiation grants, of approximately $25,000 each over six months, have been funded. In addition, a three-year, $525,000 project on sheet metal forming has been initiated.
4. The first quarterly newsletter was issued in August 1986 and an industry review meeting, with more than 120 participants, was held in September 1986.

5. Ten companies have agreed to become full members of the center at an annual fee of $25,000 per year. In addition, a $225,000 commitment for sheet metal forming research has been received from an automotive company.

6. An associate director, an administrative assistant, a post-doctoral research associate, and two full-time staff engineers have been hired, effective October 1, 1986.

We expect to reach a near steady-state mode of operation within the next four to six months. Thus, early in 1987 we expect to have enough member companies involved to staff all Advisory Boards, initiate regular research tasks, and purchase and install some of the research equipment needed for the planned research of the Center. A newly established M.S.-level Manufacturing Systems and Engineering Program (see "Education" above) starts in the fall of 1986 and is coordinated with the research and educational activities of the Engineering Research Center.

Perspectives: A Responsibility to Lead

DON E. KASH

The importance of the initiative represented by the Engineering Research Centers could hardly have been more emphatically underlined than it was the week before the symposium, when the United States became the largest debtor nation in the world. It is nothing less than astounding that in less than three and a half years the United States has moved from a position of being a net creditor nation in the amount of $152 billion, its historical high, to being a net debtor nation of $107 billion. That is a turnaround that must be historically unique in its scale and rapidity.

No view seems supported by a broader consensus than the view that this trend in our balance of payments will only be reversed with a significant enhancement of the nation's capacity to innovate technologically. The symposium on which this volume is based had the title "Engineering Research Centers: Leaders in Change." I think that was a particularly appropriate title because if the United States is to regain its technological leadership, broad and fundamental changes will be necessary. Clearly, the Engineering Research Centers cannot do the job by themselves. Nevertheless, they represent an important initiative, one whose significance is hard to exaggerate. They represent a cooperative effort among government, industry, and universities that I find very encouraging.

In my bleaker moments I sometimes think we Americans have lost our flexibility and our capacity for imagination. I find myself delighted to be at least minimally associated with this enterprise, because it represents a new initiative that I firmly believe will have a great impact. No message is clearer with regard to the technological successes of this nation, during and after World War II, than that they have required meaningful cooperation among industry, universities, and government. Other societies do it differently. This is our way.

Only institutional cooperation, linking fundamental research and training on the one side with production (the delivery of goods and services) on the other will give us the ability to compete in the future. There was a great deal of discussion during the symposium about a "culture change" in engineering. I think that is not a bad label. The culture change is required in universities, and it is required in industry, and it is required in government.

The kind of culture that allowed us to operate an industrial society with long production runs, because you could get by "giving them any color they wanted, as long as it was black," no longer exists. That point was repeatedly emphasized by speakers at the symposium.

What are we talking about when we talk about a culture change? First, within the universities we are talking about a culture change that puts an emphasis on groups rather than individuals. Paul Chenea once told me that Purdue University was 2,000 faculty members held together by parking stickers. A university is an institution designed primarily to encourage "lone rangers." It must now encourage groups. I think Alan Michaels made a critical point in his paper (see Part III): There is almost no significant technology today that is manageable by a lone ranger. Innovation and engineering are now organizational phenomena. As a matter of fact, one of the most interesting things one notices about the National Academy of Engineering is that the vast majority of the successful engineers one encounters are either public sector or private sector bureaucrats; that is, they are vice-presidents or deans or directors of research. Not infrequently, talented engineers speak of themselves as if they were Einsteins, individuals who come up with $E = mc^2$. Engineers are really the artists of our society, and they create great things; but they do it by coordinating the activities of many people from many disciplines.

I will say it again: Innovation today is an organizational product. It is a group product. We will not win with lone rangers. As a matter of fact, we cannot depend on creative geniuses for innovation because we have too few at any given time. We really must have organizations that innovate; indeed, that is just what we do have in those areas in which we are successful.

What other cultural changes are needed? For one thing, we must move from disciplines to interdisciplinary activities. There are very few technologies today that can be handled within the confines of one discipline. That is not a call for rejecting the disciplines. One critical thing about the Engineering Research Centers, however, is that they provide an absolutely essential ingredient: the organizational capability to integrate disciplines.

This change in culture is needed in the universities, to be sure, but it is also needed in industry and government. Thus, my plea to those who are involved in the Centers, whether you work for government, industry, or universities, is to *lead society*.

You cannot lead only engineering. You really have to lead society. You do your work in organizations. That is a given; it is not a choice. And if you do not lead in educating business managers and politicians—and, yes, even educating financiers as to what the nature of this technological game is—the Engineering Research Centers can end up being incredible successes in the narrow technical sense yet total failures in the broad societal sense.

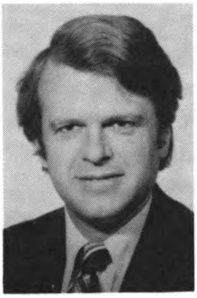
The fact is that somehow, even in those areas where we lead in invention, we lose in innovation. I suggest that one of the root causes is a system where managements must focus on bottom lines over quarterly periods; where predatory "corporate raiders" lurk in the clouds. We may have reduced the time between ideas and products from ten years to five years, but my impression is that five years is still too long for most corporate managements. They have to deliver profits on a daily basis or a quarterly basis.

Now, if in fact technology is as important as I think everyone reading this believes it to be, my plea to engineers and to engineering schools is that you have broad responsibilities which you must take seriously. You have many things to tell the people in the business schools. You may have some things to tell the people in humanities and social sciences. You are sitting on top of the engine that drives our society. If we learn how to manage that engine, the future looks pretty good. If we do not, it is grim. Remember this: We are borrowing a hundred billion dollars a year from overseas to feed consumption. We are not investing that money in capital stock. We have a society that does not know how to save and does not know how to think about anything that is very long term, yet you who are involved directly in technology development are the people who understand best that experimentation and lead time are necessary. Technology is not a deductive process. It is a process of trial and error. My final point is that we must recognize that the best thing we can do for the Engineering Research Centers is to recognize that they had better fail as well as succeed, because if they do not fail sometimes, they are not stretching their fingers very far. We had better not get into the position of trying to exercise short-term judgments about the successes or failures of these Centers.

If you who are associated with the Centers are going to be given the task of being the revolutionaries of the technological society—and that is what you are if you are trying to bring about cultural change—you are going to need some time and some freedom. I commend you! I think you are involved in the most important task this society has before it. I think that the Engineering Research Centers and the enterprises associated with them will determine historically whether this is the decline and fall of the American empire or a recharging for the future. But the needed change in our culture is not going to be achieved solely within the engineering schools. I think you engineers ought to take the task that is before you to be a revolutionary one—you are the creators of the technology that is the driving force of the future! You must also assume the obligation to educate the rest of society as to how to successfully operate the technological society.

Biographies

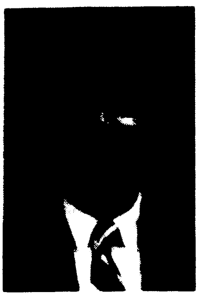
TAYLAN ALTAN is a Professor of Industrial and Systems and Mechanical Engineering at The Ohio State University and Director of OSU's newly established Engineering Research Center for Net Shape Manufacturing. He received his Diploma Engineering Degree in Manufacturing from the Technical University of Hannover, West Germany (1962), and his Master's and Ph.D. degrees in mechanical engineering from the University of California, Berkeley (1966). After 2 years at Dupont and 17 years at Battelle's Columbus Division, he joined OSU in January 1986. Author or coauthor of numerous articles and two books, he is a fellow of the Society of Manufacturing Engineers, American Society of Mechanical Engineers, and American Society for Metals and is active in the International Production Engineering Research Institute. Dr. Altan's primary technical background is in metalforming, computer-aided design and manufacturing of dies and molds, and analysis of deformation processes.



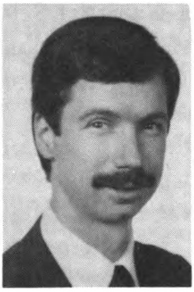
JOHN S. BARAS is Professor of Electrical Engineering at the University of Maryland and Director of that university's Systems Research Center. He received a Bachelor's degree in electrical engineering with highest distinction from the National Technical University of Athens, Greece (1970). He earned his Master's (1971) and Ph.D. (1973) degrees in applied mathematics from Harvard University. Dr. Baras has extensive experience in academic and industrial research on automatic control and communications systems. He has held visiting research scholar positions with Stanford, MIT, Harvard, and the University of California, Berkeley, and he has published numerous research articles on a variety of topics, including optical communications, queueing systems, control of distributed systems, nonlinear systems, stochastic systems, computer architecture for signal processing, optimization, and applied mathematics. Among his research awards are a 1978 Naval Research Laboratory Research Publication Award, the 1980 Outstanding Paper Award of the IEEE Control Systems Society, and a 1983 Alan Berman Research Publication Award from NRL. Dr. Baras is a Fellow of the IEEE Engineering Research and Development Committee.

ARDEN L. BEMENT, JR., is Vice-President of Technical Resources for TRW. He received his Ph.D. in metallurgical engineering at the University of Michigan in 1963. He worked in industry initially, including 10 years with General Electric and 5 years in nuclear materials research at the Battelle Memorial Institute; later he was a Professor of Nuclear Engineering (materials) at MIT. From 1976 to 1979 Dr. Bement served as Director of the Office of Materials Science at the Defense Advanced Research Projects Agency (DARPA), he was later Deputy Under Secretary of Defense for Research and Engineering. He is a member of the National Academy of Engineering and is currently Chairman of the Commission on Engineering and Technical Systems of the National Research Council.

ERICH BLOCH is Director of the National Science Foundation. He joined IBM Corporation in 1952 after receiving a B.S. in electrical engineering at the University of Buffalo (now SUNY Buffalo). He was instrumental in development of the IBM 360 computer (among other projects), for which he was awarded the National Medal of Technology in February 1985. Before coming to NSF, Mr. Bloch was Chairman of the Semiconductor Research Corporation, and served as Vice-President for Technical Personnel Development at IBM from 1981 to 1984. He is a member of the National Academy of Engineering.



CHRISTOPHER M. COBURN was appointed Executive Director of Ohio's Thomas Edison Program and Science and Technology Advisor to Ohio Governor Richard F. Celeste in August 1984. He also serves as Deputy Director of the Ohio Department of Development. Mr. Coburn is responsible for the \$160 million Thomas Edison Program, one of the largest public/private high-technology programs in the United States. Additionally, he directs three other technology programs for the state of Ohio and advises the governor on issues of science policy. He also represents Governor Celeste as the leader of the National Governors Association Working Group on State Applied Research Initiatives. Prior to his return to Ohio, Mr. Coburn was Assistant Director of the state of Ohio's Washington, D.C., office. Mr. Coburn received his Master's degree in public administration from George Washington University. He holds a B.A. from John Carroll University in Cleveland, Ohio. Mr. Coburn was selected for the prestigious Management Intern Program. He has held positions at the National Aeronautics and Space Administration and the National Institutes of Health. In addition, he has worked on Capitol Hill as an aide to Ohio Congressman Louis Stokes.



CHARLES L. COONEY is Professor of Chemical and Biochemical Engineering at MIT and is a member of the Operating Committee of the Biotechnology Process Engineering Center at MIT. Dr. Cooney holds a Bachelor's degree in chemical engineering from the University of Pennsylvania and S.M. and Ph.D. degrees in biochemical engineering from MIT (1970). He joined the faculty of MIT in 1970 and currently holds a joint appointment in the Department of Chemical Engineering and the Department of Applied Biological Sciences. Dr. Cooney has authored three books and numerous publications in his primary areas of research which include fermentation and enzyme technology, recovery of biological products, and applications of computer control to biochemical systems. He serves as a consultant and/or director of a number of companies in the biochemical process industry and is on the editorial board of several widely known journals in the field.

WILLIAM A. DICK is Deputy Director of the University of Delaware Center for Composites Manufacturing Science and Engineering. He received his B.ME. degree in mechanical and aerospace engineering from the University of Delaware. He joined the Center for Composite Materials at Delaware in 1979 as a Research Associate to direct the Composites Fabrication and Testing Laboratory. Since 1982 he has been Assistant Director, then Deputy Director, of the research center. He is the principal liaison between the Delaware Center and its industrial sponsors. Mr. Dick is a member of several composites-related technical societies, including the American Society for Testing and Materials and the Composites Group of the Society of Manufacturing Engineers. He is also a member of the American Society of Mechanical Engineers and the National Council of University Research Administrators.

JOHN W. FISHER is Professor of Civil Engineering at Lehigh University and Director of Lehigh's new Center on Advanced Technology for Large Structural Systems. He received his BSCE in civil engineering from Washington University in 1956 and his Ph.D. from Lehigh University in 1964. He has been a faculty member at Lehigh since 1964. Through his research on fatigue behavior of steel structures and improvement of design techniques and standards, he has contributed to the safety and economical design of steel bridges and buildings. He has published 140 articles and books on this work. He is a Fellow of the American Society of Civil Engineers and was elected a member of the National Academy of Engineering in 1986.

SUSAN HACKWOOD is Professor of Electrical and Computer Engineering at the University of California, Santa Barbara; she is also the Director of UCSB's Center for Robotic Systems in Microelectronics. Dr. Hackwood obtained her Ph.D. in solid state electrochemistry at Leicester Polytechnic Institute, U.K. After completing the Doctorate, she joined AT&T Bell Laboratories, where she remained until 1984. At Bell Labs she carried out a range of research in robotics, and was named Head of the Robotics Technology Research Department.

DON E. KASH is George Lynn Cross Research Professor of Political Science and a Research Fellow in the Science and Public Policy Program, University of Oklahoma. He is chairman of the Cross-Disciplinary Engineering Research Committee of the National Research Council (NRC), which organized the symposium. From 1978 through 1981 Dr. Kash headed the Conservation Division, U.S. Geological Survey. His fields of interest are energy policy, science and public policy, and policy analysis. Professor Kash has served on several advisory committees for the Office of Technology Assessment

(OTA) and presently chairs the OTA Advisory Panel on Technologies to Control Illegal Drug Traffic. He is a member of the NRC's Marine Board. He has chaired NRC studies such as Information and Technology Exchange Among Engineering Research Centers and Industry, and National Dredging Issues and has served as a member of a variety of other NRC committees. Professor Kash is the author or coauthor of seven books and 30 articles, and is currently at work on a book to be entitled *The Synthetic Society*, a study of technological innovation.

JOHN P. McTAGUE is Vice-President for Research at the Ford Motor Company. He received his Ph.D. in physical chemistry from Brown University in 1965. After working at the North American Rockwell Science Center, he joined the chemistry faculty at the University of California, Los Angeles, and had a joint appointment in the Institute of Geophysics and Planetary Physics. In 1982 he became Chairman of the National Synchrotron Light Source Department, Brookhaven National Laboratory, and Adjunct Professor of Chemistry at Columbia. Late in 1983 he was appointed Deputy Director of the Office of Science and Technology Policy, and served as its Acting Director in 1986.

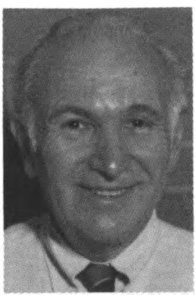
D. BRUCE MERRIFIELD, a graduate of Princeton University, holds Master's and Doctoral degrees in Physical Organic Chemistry from the University of Chicago. He is currently Assistant Secretary of Commerce for Productivity, Technology and Innovation. Formerly, he was Vice-President of Technology and Venture Management for the Continental Group. He is a former director and president-elect of the Industrial Research Institute, and is both a former Trustee of the American Management Association and Chairman of its Research Council. Currently, he is member of the Directors of Industrial Research, a member of Sigma Xi Honorary Society, and is a Fellow of both the American Association for the Advancement of Science and the Institute of Chemists. Dr. Merrifield has been an advisor in various capacities to the governments of Israel, the

People's Republic of China, and Jordan with respect to science, research, and development.

ALAN S. MICHAELS is Distinguished University Professor of Chemical Engineering at North Carolina State University at Raleigh. He was formerly President of Alan Sherman Michaels, Sc.D., Inc., an industrial consulting firm in Boston, Massachusetts. An MIT graduate, he was Professor of Chemical Engineering at that institution from 1948 to 1966, President of Amicon Corporation from 1962 to 1970, President of Pharmetrics, Inc., and Alza Research (Palo Alto) from 1970 to 1976, and Professor of Chemical Engineering and Medicine at Stanford University from 1976 to 1981. Dr. Michaels' research, teaching, and industrial management activities have been in the fields of surface and polymer science, membrane technology, separation science, and biotechnology. He is a member of the National Academy of Engineering.

RICHARD OSGOOD received his B.S. in engineering from the U.S. Military Academy in 1965, his M.S. in physics from Ohio State University in 1968, and his Ph.D. in physics from MIT in 1973. He has over 100 publications in laser and semiconductor technology and related basic physics. Dr. Osgood is a member of the Department of Electrical Engineering and the Department of Applied Physics at Columbia University; he is codirector of Columbia's Radiation Laboratory and Director of Columbia's Microelectronic Sciences Laboratory, as well as being a participant for the Center for Telecommunications Research. His research areas include development of novel electro-optical and electronic devices, development of solid-state laser sources, optical interconnect technology, and basic molecular physics and surface science research.

WALTER H. PLOSILA is Deputy Secretary for Technology and Policy Development of the Department of Commerce in the Commonwealth of Pennsylvania. Before joining the Department of Commerce, Dr. Plosila served as Director of the Governor's Office of Policy and Planning. Earlier, he was Director of Research of the Pennsylvania House of Representatives, Associate State Planning Director for the state of Kansas, and a management consultant with Westinghouse; he has worked in the federal executive and legislative branches as well as at the local government level. Dr. Plosila has served as President of the National Council of State Planning Agencies, Chairman of the Pennsylvania Intergovernmental Council, and as a member of several science and technology boards of the National Science Foundation and other groups and organizations. He has a Ph.D. in Public and International Affairs from the University of Pittsburgh.

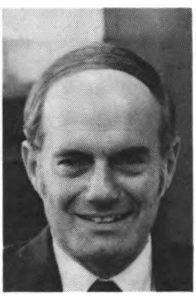


MISCHA SCHWARTZ is Professor of Electrical Engineering and Computer Science at Columbia University, where he directs the Engineering Center for Telecommunications Research. After earning a Master's degree in electrical engineering, he received his Ph.D. in applied physics from Harvard University in 1951. Dr. Schwartz was an engineer with the Sperry Gyroscope Company and Professor of Electrical Engineering at the Polytechnic Institute of Brooklyn before coming to Columbia. He is the author of numerous books and publications, and received the IEEE Education Medal in 1983. Dr. Schwartz was nominated to the IEEE Centennial Hall of Fame in 1984. In 1986 he was awarded the Grand Duhn medal by Cooper Union for achievement in science and technology. His primary research interests are in communication systems and networks, digital communications, and computer communications. He is past President of the IEEE Communications Society and a former Director of the IEEE.

L. DOUGLAS SMOOT is Dean of the College of Engineering and Technology and a Director of the new Advanced Combustion Engineering Research Center at Brigham Young University. Dr. Smoot completed his graduate work at the University of Washington in 1960. He has been at Brigham Young University since 1967 as a professor of Chemical Engineering (1970 to 1977). Previous experiences included four years at Lockheed, one year at the California Institute of Technology, and summers with Hercules, Phillips Petroleum Company, and Boeing. He has also consulted extensively in the areas of energy, combustion, and propulsion with organizations in the United States, Europe, and Asia. Research interests include dust fires and explosions, fossil fuels combustion, kinetics of coal gasification, and modeling of combustion processes. He is a member of AIChE, ASEE, AIAA, and the Combustion Institute, and has received five state or regional awards in the past five years. He has published or presented over 100 articles and has published two books. He served on the Governor's Science and Technology Advisory Council for the State of Utah, was named the 1985 Distinguished Faculty Lecturer at Brigham Young University, and the same year received the Presidential award.

JAMES J. SOLBERG is a Professor of Industrial Engineering at Purdue University and Director of the Engineering Research Center for Intelligent Manufacturing Systems. He has won numerous awards for teaching and research. Since 1975 Dr. Solberg has conducted research on the mathematical modeling of manufacturing systems. He developed a program called CAN-Q, which is now widely used by industries and universities around the nation. Dr. Solberg received his Bachelor's degree in mathematics from Harvard University, and his Master's degrees in mathematics and industrial engineering and a Ph.D. in industrial engineering from the University of Michigan. He joined Purdue in 1971 after three years at the University of Toledo.

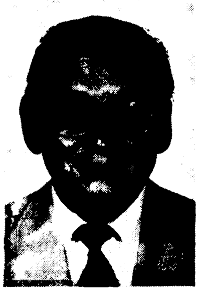
GREGORY E. STILLMAN is Director of the recently formed Engineering Research Center for Compound Semiconductor Microelectronics at the University of Illinois at Urbana-Champaign, where he is a Professor of Electrical and Computer Engineering. His research interests include characterization and crystal growth of compound semiconductors and semiconductor alloys, transport measurements on these materials, and near infrared avalanche photodiodes and related photodetectors. Before joining the Illinois faculty in 1975, he served as an officer and pilot in the U.S. Air Force. Dr. Stillman received his B.S.E.E. degree from the University of Nebraska in 1958, and his M.S. and Ph.D. degrees in electrical engineering in 1965 and 1967, respectively, from the University of Illinois. From 1967 to 1975 he was with the Applied Physics Group of MIT Lincoln Laboratory. He is a Fellow in the IEEE, and a past president of the IEEE Electron Devices Society. Dr. Stillman is a member of the National Academy of Engineering.



ROBERT STRATTON is Vice-President, Corporate Staff, and Director of the Central Research Laboratories of Texas Instruments (TI). Earlier he was Director of the Semiconductor Research and Development Laboratories. He received both his B.Sc. in physics (1949) and his Ph.D. in theoretical physics, (1952) from Manchester University, England. With TI since 1959, he has conducted a wide range of research in solid-state physics (semiconductor transport theory, hot electronics, electron multiplication, field emission, electron tunneling). Dr. Stratton has published widely in the professional journals. He is a Fellow of the Institute of Physics (Great Britain), the American Physical society, and the IEEE. He also is on the Board of Directors of the Industrial Research Institute.

NAM P. SUH is Assistant Director for Engineering of the National Science Foundation. He performed his undergraduate work in mechanical engineering at MIT, and received the Ph.D. from Carnegie-Mellon University in 1964. Before coming to NSF, Dr. Suh was Professor of Mechanical Engineering at MIT, and Director of the Laboratory for Manufacturing and Productivity there. He has been a director of several corporations involved in technology development, and he is the author or editor of a number of fundamental textbooks in engineering sciences.

SAROSH N. TALUKDAR, Professor of Electrical and Computer Engineering, is Codirector of Carnegie-Mellon University's newly established Engineering Design Research Center. He received his B.S degree at the Indian Institute of Technology and his M.S. and Ph.D. degrees at Purdue University. Dr. Talukdar worked at McGraw Edison for five years before joining Carnegie-Mellon University in 1974, where he has been Director of the Power Systems Program (1976–1983) and Director of the Design Research Center (1983–1986). His research is in the area of power systems, computer-aided design, intelligent computer-aided instruction, and expert systems.

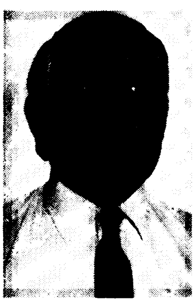


DANIEL I. C. WANG is Professor of Chemical and Biochemical Engineering at MIT and director of the Center on Biotechnology Process Engineering. Dr. Wang holds an M.S. in biochemical engineering from MIT and a Ph.D. in chemical engineering from the University of Pennsylvania (1963). He came to MIT in 1965 after two years as a process development engineer with the U.S. Army Biological Laboratories. He has authored three books, in addition to numerous other publications. Dr. Wang's primary research interests are in the molecular biology of animal cells, bioreactor design and operations, downstream processing, and biochemical process systems engineering.

ARTHUR W. WESTERBERG, Swearingen Professor of Chemical Engineering, is Codirector of the Carnegie-Mellon University's newly established Design Research Center. He received his B.S., M.S., and Ph.D. degrees from Minnesota, Princeton, and Imperial College (London), respectively. After two years with Control Data Corporation, he spent nine years on the faculty at the University of Florida. He joined Carnegie-Mellon University in 1976, where he was Director of the Design Research Center (1968–1980) and Head of Chemical Engineering (1980–1983). He has published over 90 articles in chemical process design in areas of analysis, optimization, synthesis, and expert systems, and is the recipient of national awards. He is coauthor of the book *Process Flowsheeting* (1979).

ROBERT M. WHITE is President of the National Academy of Engineering. Earlier, he was Administrator of the National Research Council. His academic background is in meteorology with a B.A from Harvard and M.S. and Sc.D. degrees from MIT. Former positions in that field include President of the University Corporation for Atmospheric Research, Administrator of the National Oceanic and Atmospheric Administration, and Chief of the U.S. Weather Bureau. Dr. White has been a member or chairman of numerous boards and committees dealing with climate, oceans, and resources. He has received many awards and honors for his contributions to science and technology.

DICK J. WILKINS, Professor or Mechanical Engineering, is the Director of the Composites Center at the University of Delaware. The Center encompasses the Center for Composite Materials (founded in 1974); the Delaware-Rutgers National Engineering Research Center for Composites Manufacturing Science and Engineering (founded in 1985); and the U.S. Army Center of Excellence for Manufacturing Science, Reliability, and Maintainability Technology (founded in 1986). Dr. Wilkins received his B.S. and M.S. degrees in aerospace engineering and his Ph.D. in engineering science (1969) from the University of Oklahoma. He spent 17 years with General Dynamics, where he was responsible for numerous technology development activities in composites, including the U.S. Air Force structural certification of the first production graphite-epoxy structures, the empennage of the F-16 aircraft. He is a member of several composites-related technical societies, including the American Society for Testing and Materials, the American Association for Artificial Intelligence, the Society for the Advancement of Materials and Process Engineering, the Society of Manufacturing Engineers, and the American Society for Composites.



MICHAEL J. WOZNY is Professor of Electrical, Computer and Systems Engineering at Rensselaer Polytechnic Institute (RPI), and Director of RPI's Center for Interactive Computer Graphics, which he established in 1977. The Center, which enjoys significant industrial support for its computer-aided design/computer-aided manufacturing research, was originally seed-funded by NSF's Industry-University Cooperative Research Centers program. Dr. Wozny was chairman of a 1983 COSEPUP (Committee on Science, Engineering, and Public Policy of the Academies and the Institute of Medicine) research briefing panel on Computers in Design and Manufacturing, out of which emerged the core concept of the Engineering Research Centers. He received his Ph.D. in electrical engineering from the University of Arizona in 1965.

NATIONAL ACADEMY PRESS

The National Academy Press was created by the National Academy of Sciences to publish the reports issued by the Academy and by the National Academy of Engineering, the Institute of Medicine, and the National Research Council, all operating under the charter granted to the National Academy of Sciences by the Congress of the United States.